



The Development of Cockpit Display and Alerting Concepts for Interval Management (IM) in a Near-Term Environment

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Preface

This document is intended to provide the aviation industry with an overview of the Interval Management (IM) research conducted over the past 15 years, lessons learned from that research, and a description of the current state of the IM displays and alerting concepts.

The authors served as editors for the section that summarized the IM research, and additional input and guidance was provided by the entire NASA Langley IM research team. In alphabetical order, the authors thank: Terence Abbott, Bryan Barmore, Clay Hubbs, Joe King, Kara Latorella, Jennifer Murdoch, Mike Palmer, Roy Roper, Jim Smail, and Sara Wilson. The authors also gratefully acknowledge the many inputs our colleagues at NASA Ames, the FAA, MITRE, Boeing, Airbus, Honeywell, and ACSS made to the IM concept and this document, as well Tim Beyer, Stuart Cooke, and Karlus Grant for creating many of the graphics used in this document.

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Abbreviations and Acronyms

ACARS	Aircraft Communications Addressing and Reporting System
ADS-B	Automatic Dependent Surveillance–Broadcast
AGD	ADS-B guidance display
AGL	above ground level
AMSTAR	Airborne Merging and Spacing for Terminal Areas
ARIES	Airborne Research Integrated Experiments System
ARP	Aerospace Recommended Practice
ASTAR	Airborne Spacing for Terminal Arrival Routes
ASTOR	Aircraft Simulation for Traffic Operations Research
ATAAS	Advanced Terminal Area Approach Spacing
ATC	Air Traffic Control
ATD-1	ATM Technology Demonstration–1
ATM	Air Traffic Management
CA5.3	CMS ATD–1 study #5.3
CDA	Continuous Descent Arrival
CDTI	Cockpit Display of Traffic Information
CDU	Control Display Unit
CGD	Configurable Graphics Display
CMS	Controller Managed Spacing
CPDLC	Controller Pilot Data Link Communications
DAG-TM	Distributed Air/Ground Air Traffic Management
DB	data base
DES	descent
DTS	Development and Test Simulator
EADI	Electronic Attitude Director Indicator
EFB	Electronic Flight Bag
EFVS	Enhanced Flight Vision Systems
EICAS	Engine Indication and Crew Alerting System display
EQUIP	equipment
ETA	estimated time of arrival
FAA	Federal Aviation Administration
FAF	Final Approach Fix

FCST	forecast
FDMS	Flight Deck-based Merging and Spacing
FIM	Flight deck-based Interval Management
FIM-DS	FIM with Delegated Separation
FLIR	Forward Looking Infrared
FMC	Flight Management Computer
FMS	Flight Management System
F/S	Fast / Slow
FOV	field-of-view
GPS	Global Positioning System
HITL	human in the loop
HUD	heads up display
IFD	Integration Flight Deck simulator
IM	Interval Management
IM-NOVA	Interval Management for Near-term Operations Validation of Acceptability
IMSACE	Interval Management Speed Awareness and Conformance
IMSPiDR	Interval Management with Spacing to Parallel Dependent Runways
I-SIM	Interface Study for Interval Management
KATL	Hartsfield-Jackson Atlanta International Airport
KDFW	Dallas Ft-Worth International Airport
KMEM	Memphis International Airport
KPHX	Phoenix Sky Harbor International Airport
KSDF	Louisville Standiford International Airport
LaRC	Langley Research Center
LNAV	lateral navigation
MCDU	Multi-function Control Display Unit
MCP	Mode Control Panel
NASA	National Aeronautics and Space Administration
NextGen	FAA's Next Generation Air Transportation System
ND	navigational display
PDS	Pair-Dependent Speed
PF	Pilot Flying
PFD	Primary Flight Display

PM	Pilot Monitoring
RFD	Research Flight Deck simulator
RTA	required time of arrival
RTE	route
SPC	spacing
SPD	speed
SPI	spacing position indicator
STA	scheduled time of arrival
STAR	Standard Terminal Arrival Route
SVS	Synthetic Vision Systems
TGT	Target aircraft
TMA-TM	Traffic Management Advisor with Terminal Metering
TOD	Top of Descent
TRACON	Terminal Radar Approach Control
VERT	vertical
VNAV	vertical navigation
WPT	waypoint

1 Introduction

1.1 Purpose of Document

The National Aeronautics and Space Administration (NASA) Langley Research Center (LaRC) Interval Management (IM) research team has conducted a wide spectrum of work in the recent past, ranging from development and testing of the concept, procedures, and algorithm. This document focuses on the research and evaluation of the IM pilot interfaces, cockpit displays, indications, and alerting concepts for conducting IM spacing operations (ref. 1). The research team incorporated knowledge of human factors research, industry standards for cockpit design, and cockpit design philosophies to develop innovative displays for conducting these spacing operations. The research team also conducted a series of human-in-the-loop (HITL) experiments with commercial pilots and air traffic controllers, in as realistic a high-density arrival operation environment as could be simulated, to evaluate the spacing guidance display features and interface requirements needed to conduct spacing operations.

Throughout this research, NASA has closely collaborated with the Federal Aviation Administration (FAA) and industry partners to develop the airborne spacing concept (ref. 2). Recently, efforts to harmonize the concept, operations, and procedures to conduct IM have gained traction, and recently published documents add a significant amount of new requirements for IM (ref. 3 and ref. 4).

The combination of responding to research results in the first paragraph, and new requirements for IM operations in the second paragraph, drove the need for a redesign of NASA's IM software logic, messages, and displays. Therefore, this document has two purposes:

- (1) to provide a high-level description of previous research and the lessons learned, and
- (2) to provide a detailed description of the current IM software logic, messages, and displays.

1.2 Background

IM is one of several airborne surveillance applications being developed by the RTCA's Special Committee 186.

The goal of IM is to improve the precision of spacing between aircraft in order to improve traffic flow and airport throughput. IM is defined as the overall system that includes both ground and airborne tools, where the ground tools assist the controller in evaluating the traffic picture and determining appropriate clearances to merge and space aircraft efficiently and safely, and airborne tools that allow the flight crew to conform to the IM clearance (Annex A of ref 3).

Throughout this paper, the term Ownship will be used to reference the aircraft that is equipped with the IM spacing software and displays (or conducting the IM operations), and the term Target will be used to reference the aircraft the Ownship has been assigned to follow.

1.3 Guiding Principles

The guiding design principals are grounded in aerospace recommended practice (ARP) from the SAE S-7 committee for Flight Deck and Handling Qualities Standards for Transport Aircraft, the SAE G-10 committee for Aerospace Behavioral Engineering Technology, the Federal Aviation

Administration (FAA) Advisory Circulars, and the RTCA SC-186 Minimum Operational Performance Standards (MOPS) and Minimum Aviation System Performance Standards (MASPS) for Automatic Dependent Surveillance–Broadcast (ADS-B) and cockpit display of traffic information (CDTI).

Industry standards used by the IM research and development teams include

- ARINC 726 Flight Warning Computer System
- DOT/FAA/TC-13/44 Human factors considerations in the design and evaluation of flight deck displays and controls
- FAA AC 25-11A Electronic flight deck displays
- FAA AC 25.1322-1 Flight crew alerting
- FAA AC 25.1329-1B Flight guidance systems
- MIL-STD-1472G DoD design criteria standard human engineering
- RTCA DO-317B Minimum Operational Performance Standards (MOPS) for Aircraft Surveillance Applications (ASA) System (by SC-186)
- RTCA DO-338 Minimum Aviation System Performance Standards (MASPS) for ADS-B Traffic Surveillance Systems and Applications (ATSSA)
- SAE S-7 ARP 4101 Flight deck layout and facilities
- SAE S-7 ARP 4101/4 Flight deck environment
- SAE S-7 ARP 4102/4 Flight deck alerting system
- SAE S-7 ARP 4102/7 Electronic displays
- SAE S-7 ARP 4103 Flight deck lighting for commercial transport aircraft
- SAE S-7 ARP 4102/5 Primary flight controls by electrical signaling
- SAE G-10 ARP 5365 Human interface criteria for cockpit display of traffic information

While developing the IM displays, the LaRC IM research team incorporated the standards and recommended practices above and employed the following design principals to create displays aimed at preventing and mitigating human error:

- Provide pilots with all the necessary information to safely conduct airborne spacing.
- Minimize the workload associated with conducting IM operations.
- Display information to control or maneuver the aircraft within the pilot's primary FOV.
- Restrict support information to auxiliary displays located outside the primary FOV to preserve the saliency of information presented within the primary FOV.
- Make changes to the IM-commanded air speed salient without distracting pilots from operating the aircraft safely.
- Annunciate mode changes and speed changes in the primary FOV.
- Minimize the number and types of IM system alerts.
- Minimize the number of operational modes of the IM system.
- Provide an appropriate degree of automation and alerts for safe operation of the aircraft.
- Provide system monitoring and alerting to keep the pilot fully aware of changes.

2 Overview of Previous Airborne Spacing Research

2.1 Airborne Precision Spacing Operational Concept

This section covers a portion of the NASA experiments and one of several MITRE experiments that used airborne spacing concepts where the intent was to use existing cockpit displays, or where advanced integrated avionics were expected to be available. This research was conducted throughout the 2000s and early 2010s, and examples of this include the use of Controller Pilot Data Link Communications (CPDLC), the airborne spacing algorithm integrated into the aircraft flight management system (FMS), the use of auto-throttle to implement the changes in commanded speed from the spacing algorithm, the speeds to achieve the assigned spacing integrated into the electronic attitude director indicator (EADI) and navigation display (ND), and the flight crew assuming responsibility for aircraft separation. This research also tended to focus heavily on the airborne component of the concept, and did not employ a robust and dynamic ground component. (The more recent ATD-1 research described in the next chapter assumes retrofit-avionics that are not completely integrated into the cockpit, CPDLC and other advanced features do not exist, and more sophisticated ground systems were integrated into that concept and those experiments.)

The concept of airborne precision spacing operations in terminal area arrival flows has evolved from several decades of research into aircraft-managed spacing, with earlier research indicating that by precisely spacing aircraft at the runway threshold, the variability in threshold crossing time could be reduced, thereby increasing runway throughput. Further, even a small increase in runway throughput should lead to a decrease in landing delays for airports during high-demand conditions. Research at NASA LaRC established the feasibility of using traffic information displayed on the flight deck to enable airborne-managed precision spacing. This phase of research also determined that time-based spacing was superior to distance-based spacing due to the successive speed reductions that are inherent in arrival flows.

In 1999, NASA researchers developed a preliminary concept of operations for terminal area precision spacing where the air traffic controller delegates responsibility for spacing at the runway threshold to the flight crew, while the controller retains responsibility for separation and for issuing the spacing instruction to the flight crew. Airborne automation assists the flight crew in achieving this task through a control law that provides an airspeed to the flight crew. This preliminary concept utilized a spacing error, where the spacing algorithm calculated the estimated time-of-arrival (ETA) at the achieve-by point for both IM and Target aircraft (the aircraft that will immediately precede the IM aircraft at the achieve-by point) along their respective routes, then compared that difference to the assigned spacing goal. This spacing error value was then used to calculate the IM commanded speed that the flight crew would fly.

2.2 Advanced Terminal Area Approach Spacing (ATAAS)

NASA's Advanced Air Transportation Technologies Project developed the concept of Distributed Air/Ground Air Traffic Management (DAG-TM). The DAG-TM concept used a collaboration of airborne and ground-based resources to enable less restricted and more efficient aircraft trajectories throughout all phases of flight, leading to increased airport capacity. The element of

the DAG-TM concept that focused on terminal area operations required the development of technologies and procedures that allow aircraft more flexibility in choosing an efficient route through the terminal area while arriving at the runway threshold properly spaced from the preceding aircraft. This research focused on increasing spacing precision to achieve the assigned spacing goal at the runway threshold, and an operational concept, speed guidance algorithm, and pilot display symbology were developed (refs. 5 and 6).

The ATAAS algorithm was designed to provide pilots with speed guidance which, when properly followed, would result in the correct spacing interval behind the lead aircraft at the runway threshold. Supporting pilot interface and display elements provided information on the mode of operation and the state of the ATAAS-equipped aircraft, i.e., the Ownship, relative to the aircraft it is spacing behind. To achieve the concept goals for system-wide efficiency, the ATAAS algorithm was developed with features and limits on the speed guidance it provided. Commanded speed would not deviate greater than 10% of the nominal speed for any given segment on the arrival, and speed commands were also limited to prevent exceeding flap and landing gear maximum airspeed limits. A line immediately above or below the commanded speed was used to indicate to the crew when this speed limiting occurred (above the speed meant a higher speed was desired, and below meant a lower speed was desired).

The ATAAS experiment was conducted in 2001 to evaluate the concept from the standpoint of pilot acceptability, head-down time, and workload, as well as to validate the results of a Monte Carlo analysis of the ATAAS algorithm.

2.2.1 Environment and Aircraft

The facility used for this experiment was the NASA LaRC Integration Flight Deck (IFD) simulator. The IFD simulator cab is designed to represent the conventional flight deck of a Boeing 757 airplane. The cab was populated with flight instrumentation, including the overhead subsystems panels, to replicate the B-757.

A conventional Boeing 757 EADI display format, with a fast/slow (F/S) pointer and scale on the left side of the display, was used for this experiment (Figure 1). Modifications were made on the F/S pointer and scale to provide ATAAS guidance to the crew. The command airspeed bug on the electro-mechanical airspeed indicator also tracked the ATAAS speed guidance giving the pilots another reference. In addition, the ATAAS-commanded speed appeared in digital form next to the pointer on the F/S indicator in green font. When ATAAS commands were not being generated, the F/S pointer and scale worked in the conventional manner by indicating a ± 10 kt airspeed variance from the airspeed selected on the mode control panel (MCP) and shown on the electromechanical Mach/airspeed indicator with the command airspeed bug.



Figure 1. EADI with ATAAS symbology.

Symbology was added to the ND to provide additional information on the ATAAS guidance and aircraft spacing status (Figure 2). Three main pieces of information were provided:

- (1) a data block that included the selected ATAAS lead traffic's aircraft identification and the range in nautical miles from the Ownship,
- (2) a spacing position indicator (SPI) which provided the pilot with a reference of the Ownship's position relative to the optimal position based on the entered spacing interval, and
- (3) the Target aircraft's position was highlighted, and a series of dots were used to indicate the history of the Target aircraft's trajectory (expected to be useful if instructed to follow the Target aircraft, however this was not tested in this experiment).

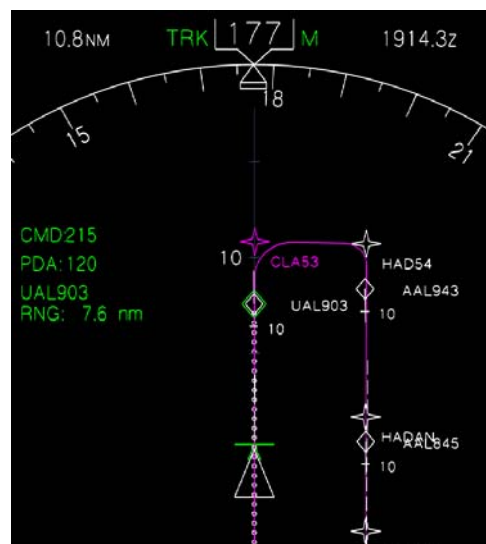


Figure 2. ND with ATAAS symbology.

The SPI was provided to show the position where the Ownship would be if the predicted spacing interval at the runway matched the desired interval (based on the current speeds and anticipated speeds for remaining flight-path segments). The indicator consisted of a short green line perpendicular to the Ownship's ground track, with an inverted "V" attached to the midpoint of the line. When the predicted and desired intervals matched, the SPI fit exactly over the apex of the white triangular Ownship symbol. If the SPI was behind the apex of the Ownship symbol, the predicted spacing was less than the assigned spacing interval. Conversely, if the SPI was ahead of the Ownship symbol, then the predicted spacing was greater than the assigned spacing interval. This indicator was intended to provide a simple visual reference of the spacing interval predicted from current conditions relative to the desired spacing interval.

The SPI was provided for situation awareness only and the pilots were instructed not to use it for any form of speed control. Details for the implementation of the symbology used in this concept and experiment are provided in reference 4.

The ATAAS symbology on both EADI and ND appeared only after a lead aircraft and spacing interval were selected from the control display unit (CDU) page. The flight crew interface with the ATAAS system was accomplished through customized flight management computer (FMC) CDU pages, accessed through a re-mapped function key on the CDU, which was labeled "ATC." The data the pilot was required to input into the custom CDU pages to enable activation of the ATAAS system were the Target aircraft identification, the assigned spacing interval, the airport winds, the final approach speeds of the Ownship and Target aircraft, and the minimum allowable spacing interval (Figure 3). The ATAAS interface tasks to make the required inputs to the research CDU would normally be done by the non-flying pilot, but in this case they were performed by a research engineer situated on the flight deck.

APPR SPACING 1/1 SELECT LEAD <PROF SPEED AAL143> AAL225> COA285> SWA281> UAL903> APPR DATA>	APPR SPACING 1/1 LEAD AIRCRAFT <NEW LEAD UAL903 CURRENT SPACING 128SEC SPACING INTERVAL 120SEC CURRENT DISTANCE 7.8 LEAD GROUND SPEED 271 KTS APPR DATA>	APPR DATA APPROACH SPEEDS NASA557 135 KTS UAL903 140 KTS MIN DISTANCE 4 NM APPROACH WINDS 180 /19 APPR SPACING
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Figure 3. CDU pages to enter ATAAS information.

The left panel of Figure 3 shows what the ATAAS custom CDU page looked like when the "ATC" function key was depressed. Nearby aircraft are listed on the right side of the display, e.g., AAL143. After line-selecting UAL903 and entering the required spacing interval (120 sec), the center panel of Figure 3 shows the current spacing interval (128 sec), current distance (7.8 nautical miles), and lead groundspeed (271 kt). These data were updated continuously. The rest of the approach data were entered on the approach data page, accessed from bottom right line-select key, shown in the right panel of Figure 3.

Eye-trackers were also used in the experiment to record the subject pilot's eye movements to ascertain that the use of the ATAAS tool was not detrimental to the pilot's out-the-window scan (ref. 6).

2.2.2 Procedures

Eight airline pilot test subjects were used in this test. Each subject pilot flew as the Pilot Flying (PF) in the left seat, with a confederate pilot (a member of experiment team) in the right seat. The confederate pilot was a retired airline pilot from a major air carrier and had previous experience as a participant in research studies at LaRC. Because crew interactions were not a focus of this study, this crew arrangement provided the opportunity to obtain data on acceptability and workload from the subject pilot while still maintaining the realism of operating in a two-person crew, full-mission environment.

The simulated environment for this study was the Memphis International Airport (KMEM) and surrounding terminal area. Calm wind conditions and visibility of 10 mi in haze were simulated. The traffic level corresponded to what might be expected at a busy terminal area. Normal radio communications with ATC were provided. Other traffic was generated from pre-recorded tracks and shown on the Ownship displays and the visual out-the-window computer-generated imagery system. The routing flown for the scenario was a modified WLDER4 standard terminal arrival route (STAR). Modifications to the STAR include a published downwind and base leg routing for a transition to the final approach course for runway 36 right. The same flight scenario was used for all runs and began with the aircraft level at 8000 ft, 250 kt, and approximately 10 nautical miles prior to the downwind turn. Figure 4 shows the displays in the ATAAS "active" mode. In this state, the commanded speed would be followed automatically if the autothrottle was on, or manually with pilot inputs to the throttles if the autothrottle was off.

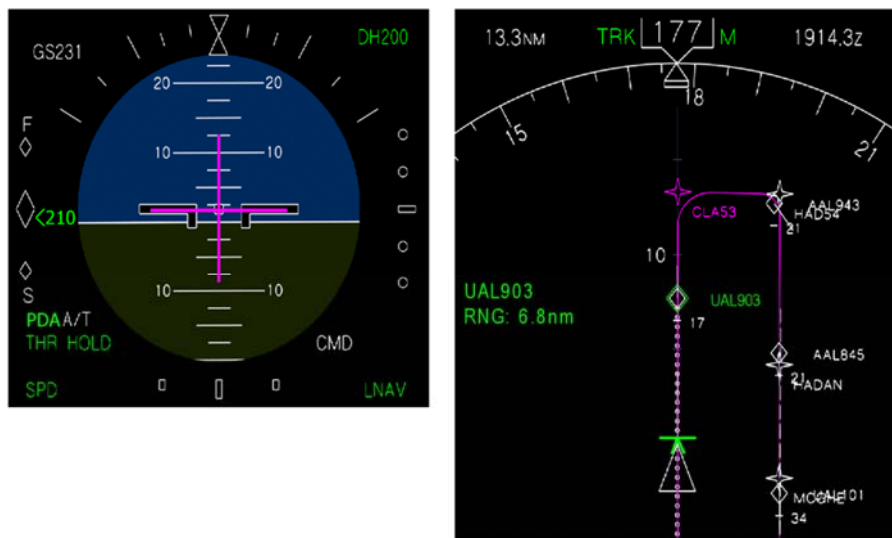


Figure 4. EADI and ND with ATAAS in ACTIVE mode.

A single stream of arriving traffic was simulated and used for all runs (i.e., call signs of the aircraft in the arrival stream were the same for all runs). The subject aircraft, NASA 557, was the eighth aircraft in trail to the runway at the start of the scenario. The traffic to follow aircraft (or traffic aircraft) was UAL903, and was immediately ahead of NASA 557. All aircraft in the scenario followed the nominal charted speeds in an orderly manner, with no unusual or rapid changes in speed. The approach spacing clearance was issued after the aircraft had turned onto the downwind leg and was on the approach control frequency (the normal approach clearance was separate from the approach spacing clearance and was issued when the aircraft was on base leg). The traffic to follow aircraft and the spacing interval were the same for all runs.

2.2.3 Results

The subject pilots generally rated the workload level with the ATAAS procedure as similar to that with standard arrival procedures. They also rated most aspects of the procedure highly in terms of acceptability (though it should be noted that the scenarios reflected a nominal environment, with no winds or abrupt changes in lead aircraft speed). The subject pilots indicated that the head-down time was slightly higher but acceptable when using the ATAAS tool. Data showed the aircraft was able to consistently achieve the assigned spacing interval when the ATAAS speed command was coupled to the auto-throttle. With the speed controlled by the pilot through the MCP or manual throttle inputs, the mean spacing interval was slightly greater, but the consistency (standard deviation) was on the same order as in the auto-throttle condition. This effect is a result of pilot response to the annunciated speed commands and could be mitigated by training or display changes to encourage the pilots to follow the ATAAS speed guidance more closely.

Regarding the EADI display symbology, the pilots were asked to rate the effectiveness of the F/S indicator on the EADI in communicating the relative speed of the two aircraft. The subject pilots rated the F/S display symbology to be borderline effective, but there was wide variability in the responses. When asked which piece of symbology should be removed, two pilots mentioned the F/S indicator. Most pilots rated the effectiveness of the commanded speed (above the F/S Indicator) considerably higher, with only one “borderline” rating. Two of the pilots indicated that they would like to see the commanded speed flash longer than 5 sec, and one of them suggested it blink until the speed was changed.

Regarding the ND symbology, the subject pilots were asked how effective the SPI was in communicating whether they were early or late relative to the lead aircraft. The mean value for this question indicated that the subject pilots judged this display symbology to be slightly effective, but the high standard deviation indicated that there was wide variation in opinions among the subject pilots. Comments about the effectiveness of the SPI were positive: it was a very good, clear symbol; it provided excellent situation awareness; and the pilot relied on it for “proof” that the system was working; Other pilots indicated that they could have flown without it, and it was only included in their instrument scan at a low level.

All subject pilots gave high ratings to the effectiveness of the commanded speed on the ND in communicating whether the Ownship was fast or slow relative to the lead aircraft, and the “flashing box” used to communicate a speed change, although one pilot commented that it should be bigger to avoid confusion with ground speed. Most pilots also gave high ratings for the effectiveness of the green outline used to highlight the traffic to follow aircraft symbol. Other comments included that it might pose a problem with a lot of green from weather radar in the background, and that it

would be better to display the lead aircraft speed under its call sign to make it easier to determine the relative speed.

High ratings were given for the acceptability of the amount of ATAAS symbology on the ND, indicating that they did not consider it cluttered. When asked what information they would add to the display, three pilots asked for the speed of the lead aircraft, two for the actual time in-trail, and one for wind data. When asked what information they would remove from the display, three pilots indicated that they would remove the SPI.

Eye-tracking data indicated that the amount of time spent scanning out the window was not significantly changed when pilots used the ATAAS procedure versus nominal procedures. In general, the pilots' scan did not appear to exhibit a definable sequence of eye movements from one area of interest to another, since the link values were nearly equivalent in either direction. This was equally true of both ATAAS and baseline conditions. The introduction of ATAAS did not result in any unusual or different eye movements between instruments as compared to the Baseline display condition.

2.2.4 Impact

The following observations influenced the design of IM displays used in subsequent research:

- The F/S symbology was deemed to be only borderline effective, especially if the change in speed is performed via the auto-throttle.
- Flashing of the speed command at a speed change should be longer than 5 seconds, and possibly should blink until the aircraft's speed was changed.
- The outlining of the symbol for the selected Target aircraft was rated highly effective.
- The usefulness of the particular SPI used in this experiment was questionable. Comments varied between it provided excellent situation awareness to it was not useful or needed.

2.3 Flexibility of Airborne Precision Spacing (FLAPS)

The Airborne Merging and Spacing for Terminal Areas (AMSTAR) concept expanded the ATAAS concept (spacing on final approach) by assigning arriving aircraft a route from terminal airspace entry to the landing runway, including the instrument approach procedure. These routes consisted of a lateral path, a nominal vertical path, and a speed profile, and could be either in trail or merging with other arriving aircraft. The route was used as a reference trajectory by the spacing tool. AMSTAR used the Target aircraft's ADS-B reported position to compute the Target's time to the runway threshold, and the same calculation was done for the Ownship aircraft. The difference between the Target and Ownship ETA at the runway threshold was compared to the ATC assigned spacing value, yielding a spacing error. The Ownship's speed was then calculated based on this spacing error; and similar to the ATAAS concept, the speed commands would not deviate beyond $\pm 10\%$ of the nominal charted speed for any given segment on the arrival. Several refinements were also made to promote the acceptability for both the pilot and the controller and for the stability of the overall operation.

2.3.1 Environment and Simulator

The FLAPS experiment was performed in 2004 at the NASA LaRC Air Traffic Operations Laboratory. The airspaces used in this experiment were Northern California TRACON, Chicago TRACON, and New York TRACON (ref. 7). Arrival routes were defined as FMS arrival routes that were based on published STAR or area navigation procedures that were extended to intercept the final approach course. The goal was to use current arrival procedures and connect them to approach procedures to create a continuous route from TRACON entry to the runway.

Each scenario consisted of two subject controllers, six subject pilots, and three confederate pilots. One confederate pilot led the stream and flew an arrival profile without any spacing clearance. The subject pilots were active line pilots from major commercial or cargo airlines with recent experience in Boeing glass cockpits. The controllers were active controllers from a range of medium to hub-sized TRACONs. Two sessions were run involving a total of twelve subject pilots and four controllers.

All subject pilots flew the Aircraft Simulation for Traffic Operations Research (ASTOR) simulator. The ASTOR is a medium-fidelity simulator, equipped with cockpit displays similar to the Boeing 777 aircraft, and employed pilot interfaces to be operated by a single pilot. ASTOR components include a six degree-of-freedom aerodynamics model, a Primary Flight Display (PFD) and ND, autopilot and auto-throttle systems, an FMC, a Multi-function Control Display Unit (MCDU), an MCP, voice communication, ADS-B, and AMSTAR.

The AMSTAR mode and guidance information was placed on the PFD and ND for this experiment. AMSTAR status and mode information appears as a small text block toward the upper right corner of the PFD (Figure 5). When AMSTAR is the active source of speed guidance, the speed Target and bug on the speed tape are green. The pilot was able to select AMSTAR as the source of speed guidance using a new mode control button placed on the mode control panel. This new speed guidance mode was called pair-dependent speed (PDS). (Note: In subsequent sections, this is referred to as the IM speed.)



Figure 5. PFD and ND for AMSTAR.

The ND showed traffic information and provided situation awareness for the spacing operation. The Target aircraft is highlighted with a green outline. A small text block appears on the middle of the left side showing the call sign of the Target aircraft and its slant distance range. At small enough map range settings, a series of dots appear behind the reference aircraft indicating its lateral path. The final addition to the ND was a spacing position indicator that showed where AMSTAR was guiding the aircraft to. The SPI marked the position of zero spacing error, and provided the pilots with situation awareness about the prediction of arriving early or late at the runway threshold. The pilots were instructed to follow the speed guidance presented on the PFD and use the ND information only for situation awareness.

Several alerts and messages were available to notify the crew of abnormal or unexpected events during the spacing operations. The most common and relevant for this experiment was a “PDS DRAG REQUIRED” message which appeared when the aircraft was more than 5 kt above the commanded speed and deviated more than 400 ft from the vertical profile. This limitation was chosen to match the limits of the vertical deviation indicator located on the ND. In these cases, the flight crew would generally need to use speed brakes to regain the speed or the vertical path.

2.3.2 Procedures

The AMSTAR training introduced the pilot interface and display modifications as well as the procedures necessary to fly the spacing operation. Possible failure modes and alerts were presented along with the expected pilot response. Two practice runs were then flown. All pilot training was done in Dallas Ft-Worth (KDFW) airspace so as to not skew the pilots’ performance in the data collection airspaces.

The pilots were instructed to follow all clearances given by the controllers, accept the spacing clearance, engage the AMSTAR tool, and follow the speed guidance provided by AMSTAR. They then monitored the speed and ensured their aircraft was properly configured for landing. The pilot’s data run ended after crossing the runway threshold but before touchdown. The pilots had the flexibility to either follow the vertical path using the FMS’s vertical navigation (VNAV) or with flight level change as they felt comfortable or as their individual company policies recommended. Objective performance data was collected for the aircraft, and the pilots completed a questionnaire following each data run.

The controllers were brought in to assist in issuing clearances and evaluating the traffic behavior. The controllers were given a computer display that showed the airspace sectors, the traffic, and the active arrival routes. Each aircraft had an enhanced data tag that showed the assigned spacing and the call sign of their lead aircraft. The controllers could also display trend vectors for each aircraft. No additional tools were available to assist in monitoring the spacing conformance. The scripted sequence of aircraft along with the expected arrival route were given to the controllers before each data run. These resembled paper scripts where the controllers could make notes.

The clearance to begin spacing operations contained two key pieces of information: the reference aircraft and the assigned spacing interval. The pilot would start by selecting the custom MCDU pages that allowed inputs to the AMSTAR tool (Figure 6). The pilot could select his reference aircraft from a list of all aircraft within ADS-B range. Once the reference aircraft was selected, the pilot would enter the spacing interval. If the reference aircraft was found, AMSTAR would go into armed mode; otherwise, AMSTAR would go into profile mode until the reference aircraft was located.



Figure 6. MCDU for AMSTAR.

2.3.3 Results

All aircraft were assigned a spacing interval of 120 sec. Across all conditions, the measured inter-arrival spacing was 119.2 ± 4.7 sec (mean \pm standard deviation) (Figure 7). The standard error was 0.5 sec. The standard deviation was larger than expected based on previous simulations where the pilots were able to achieve precision of ± 2 sec. As will be shown below, much of this larger spread is attributable to significant flight deviations resulting from the pilots' understanding of the ASTOR simulator and how to operate it. In fact, when the two most extreme outliers are removed, both of which had significant flight deviations, the standard deviation is reduced to 3.5 seconds.

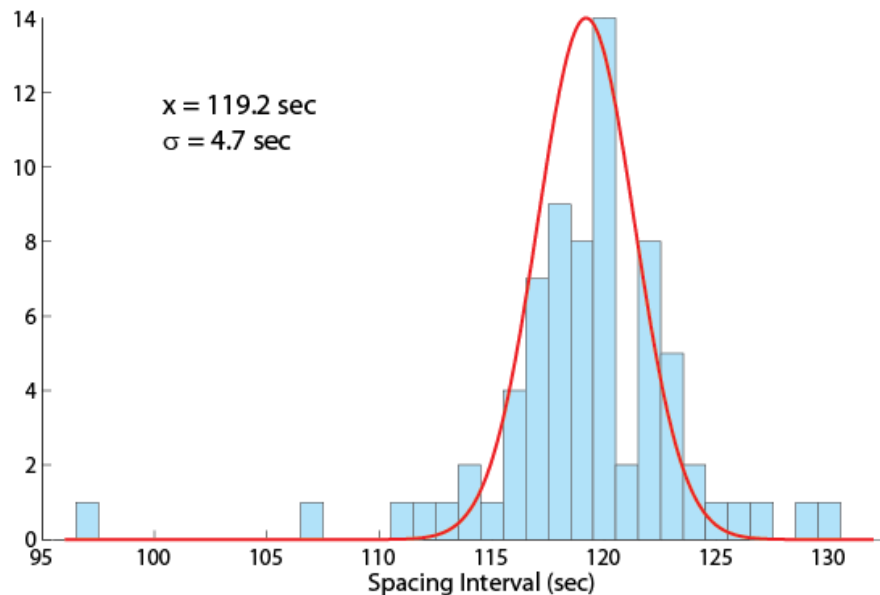


Figure 7. AMSTAR inter-arrival spacing between aircraft at runway (in sec).

To determine the number of additional speed changes, the total number of speed commands issued by AMSTAR was counted, and then the number of speed changes associated with the published arrival and approach procedures was subtracted from that total. On average there were an additional 5.9 ± 2.6 speed changes per arrival operation. The magnitude of the change in speed command was not capped, and was typically between 5 to 10 kts.

2.3.4 Impact

The overall results were positive and supported the feasibility of these types of operations. Ideas for future experiments and displays include

- define and recruit based on more stringent pilot qualification criteria;
- provide more extensive pilot training, particularly in VNAV procedures.

The following observations influenced the design of IM displays used in subsequent research:

- operations conducted during the ATAAS experiment that benefited from the history dots were not conducted in this experiment, therefore without that operational need, the use of history dots caused clutter in high-traffic environment and should be removed;
- the range to the Target aircraft was reported as not used and should be removed;
- the SPI (the “picnic table” in this experiment) was rated by the pilots as “not useful” and occasionally caused the pilots to over-control the aircraft, therefore should either remove the current version of the display or develop a more salient display.

2.4 Flight Deck Merging and Spacing (FDMS)

In 2005 NASA LaRC was invited to join a government-industry working group led by the FAA. The Flight Deck Merging and Spacing (FDMS) HITL experiment conducted at NASA LaRC in 2008 was in support of this partnership (refs. 9 and 10). This research expanded the FLAPS concept by extending the trajectory prediction from the runway to cruise altitude (FLAPS used the TRACON Meter Fix). The first objective of this study was to assess pilot acceptability of the FDMS procedures during both nominal and off-nominal events. The second objective of this study was to determine if pilots were able to execute the FDMS procedures.

The cockpit spacing technology and procedures were incorporated into the IM concept, which now addressed two important challenges to aircraft operations: reducing fuel consumption and environmental pollution generated by aircraft, while simultaneously increasing the capacity at high-density airports and the airspace surrounding them. In this experiment, ATC delegated control of the aircraft’s speed to the flight crew to achieve an assigned inter-aircraft spacing, however the concept was expanded to include the aircraft flying a Continuous Descent Arrival (CDA), which addressed both capacity and efficiency issues facing the air transportation system.

2.4.1 Environment and Simulators

The basic scenario for this test was designed to match the CDA flight-trials conducted by UPS at the Louisville Standiford International Airport (KSDF) in 2007 and 2008. Each simulator aircraft started at a point prior to the top-of-descent (TOD), flew a CDA, then intercepted the final approach course to runway 17R at KSDF. The crew was issued an IM clearance that included the Target aircraft identification and the assigned spacing interval, which was to be achieved by the

runway threshold. Two east-bound arrival streams were used, with the aircraft merging onto a single CDA prior to TOD. Each scenario consisted of eight aircraft, all piloted by subject pilots/crews, and was designed to provide a minimum of five nautical miles separation at the runway threshold (intended to represent the wake vortex separation criteria). Seven of the eight aircraft simulations were flown by an individual pilot using the ASTOR simulator. The eighth aircraft employed the full mission, high-fidelity IFD simulator with subject pilots operating as a two-person crew. A total of 26 commercial airline pilots participated in the experiment.

Figure 8 shows the PFD and ND used by the ASTORs during the FDMS experiment. The only additions to the basic B-777 type displays were the IM mode (PDS FINAL in this example) and speed (128) shown in the upper right of the PFD, and outlining the Target aircraft in green on the ND. Data entry of the IM clearance was done via a page on the MCDU (not shown).



Figure 8. ASTOR PFD and ND during FDMS experiment.

A tertiary objective of the FDMS experiment was to evaluate IM operations across a range of aircraft equipage levels, therefore the ASTOR platform emulated advanced technology aircraft with integrated avionics, while the IFD emulated current technology aircraft with limited avionics. To remain consistent with that objective, two different CDTI standards were used, with the ASTOR CDTI using chevrons and the IFD using diamonds to display other traffic. Figure 9 shows the PFD and ND used by the IFD during the FDMS experiment. Based on the Boeing 757 displays, the additions were the IM speed and mode (280 PAIR in white text) in the upper left of the PFD, and the Target aircraft ID (NA917 outlined in green) on the ND.

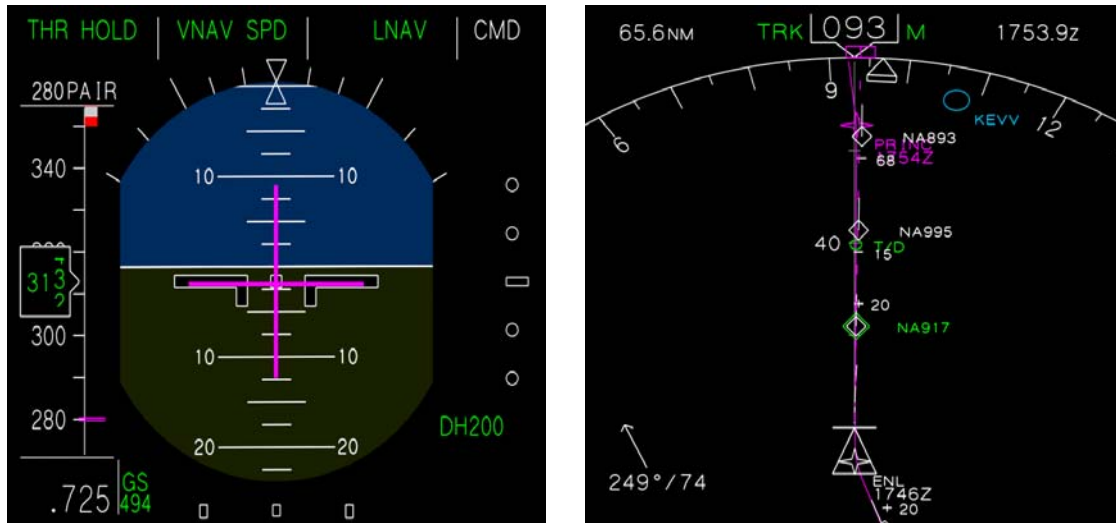


Figure 9. IFD PFD and ND during FDMS experiment.

2.4.2 Procedures

During the FDMS HITL study, the IM clearance was sent via CPDLC, which the pilots were then expected to enter the assigned Target's flight number and spacing interval in a special MCDU page. Forecast en-route and terminal area winds were entered into ASTAR via data-link. IM speed guidance was presented to the crew on the PFD and pilots used "speed intervention" and overrode the FMS speed guidance by entering the IM speed into the MCP speed window. After crossing the Final Approach Fix (FAF), the IM speed guidance displayed the planned final approach speed. This was done to facilitate achievement of stabilized approach criteria. Autopilot and auto-throttle were used by all aircraft in this test.

The IM speed guidance is designed such that the assigned spacing interval between the lead aircraft and the spacing aircraft will be achieved by the spacing aircraft at the runway threshold. The speed guidance was bounded to be within 10% of the published CDA speeds and to meet the 250 kt restriction below 10,000 ft mean sea level.

2.4.3 Results

Twenty-five of the 26 pilots responded that the FDMS procedures represent an acceptable workload trade-off compared with current day operations, e.g., ATC issuance of speed and heading changes. The majority of the pilots (92%) had no difficulty interfacing with the spacing tool, and 81% reported following the spacing tool's commands without error.

This study's arrival procedure had five planned speed changes including the deceleration to the final approach speed. Not counting the Mach calibrated airspeed transition or the commanded speed when the spacing tool was started, the flight crews saw a median of six additional speed changes with an inter-quartile range with extreme values of 1 and 12. With flight times between 23 and 42 min, this resulted in an average of one change every five minutes with a maximum of one change every two minutes, which the pilots rated as acceptable and low workload.

Of the 138 arrivals where a viable IM clearance was issued to a subject pilot, in 119 of those runs the pilot was able to follow the spacing guidance to the runway threshold. In the remaining 19 runs the IM operation was terminated prior to the runway due to excessive spacing errors (usually a result of excessive deviation in speed or vertical path by the pilot), or the pilot having difficulty making the simulator properly intercept and fly the final approach. The measured inter-arrival time is the difference between when the lead and spacing aircraft crossed the runway threshold, and the distribution is shown in Figure 10.

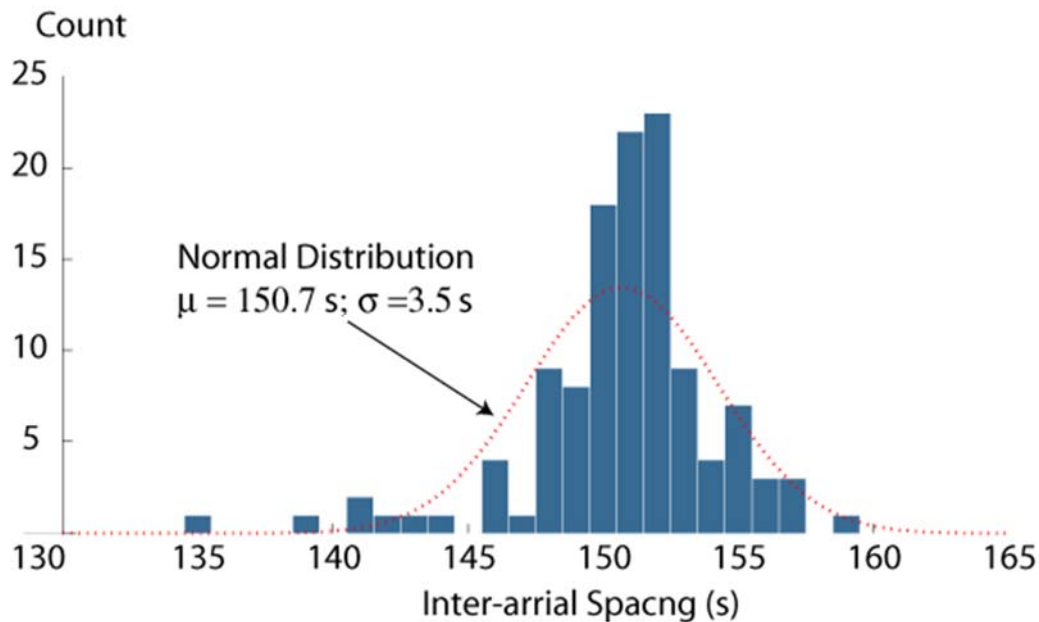


Figure 10. FDMS inter-arrival spacing at runway between aircraft (in sec).

2.4.4 Impact

The following observations influenced the design of IM displays used in subsequent research:

- The basic symbology on the ND for ADS-B traffic was shown to be acceptable.
- The placement of IM-commanded speed in the upper right corner of the ASTOR's PFD did not comply with industry standards established by SAE-S7. As a result, IM speed commands were moved to the left side of the PFD and more fully integrated with the PFD speed tape in subsequent HITL experiments (similar to PFD of IFD in this experiment).

2.5 Airborne Precision Spacing for Dependent Parallel Operations Interface Study

This 2010 study examined the usability of proposed cockpit interfaces to support IM operations for aircraft performing dependent parallel approaches. Subject pilots observed recorded simulations using the proposed interface elements in which the Ownship managed assigned

spacing intervals from two other arriving aircraft. Simulations were recorded using the ASTOR platform, and various combinations of the interface elements were presented to subject pilots. Two interface concepts were designed: 1) a fully integrated avionics suite suitable for a typical modern glass cockpit, and 2) an EFB for a retro-fit solution when the avionics suite cannot be fully integrated. The study sought to maximize the insight gained from the pilot evaluations by developing alternative versions of the interfaces such that pilots could make comparisons and express preferences for either individual design elements or combinations of the elements.

2.5.1 Environment and Simulators

The ASTOR platform was utilized to implement and display these concepts for the study. Concepts were developed which would modify the operation of several typical glass cockpit displays, interfaces, and their underlying control software. These concepts were implemented in a special ASTOR software build created for the study to support simulations, and included modifications to the Engine Instrument & Crew Alerting System (EICAS), the MCP, the MCDU, the PFD, and the ND.

The focus of the study was to obtain pilot evaluations for the design elements developed for the PFD and the ND. The modifications made to the EICAS, MCP, and MCDU were necessary to integrate the IM operations to parallel runway operation and enhance the realism of the spacing scenarios presented on the ASTOR, but were not the focus of pilot evaluations.

For the integrated avionics approach, several different options were explored to present data needed to conduct IM operations to parallel dependent runways. The left panel of Figure 11 shows the IM speed in text at the upper-right of the PFD, and the right panel shows the same information as a speed bug on the vertical speed tape.

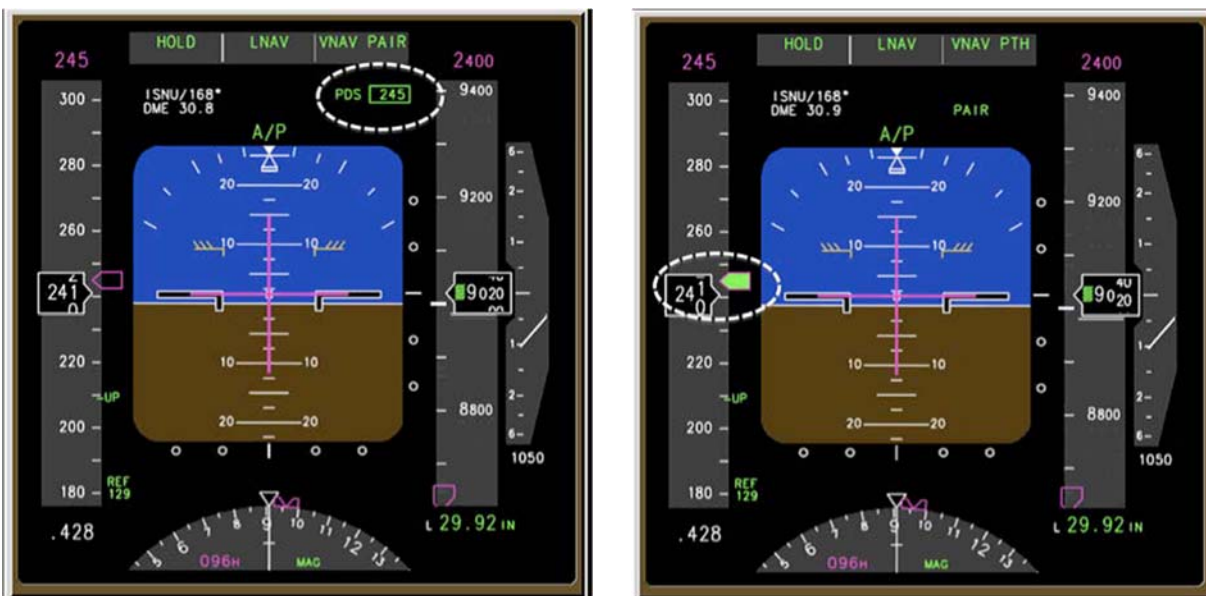


Figure 11. IM text (left) and speed bug (right) displays during the interface study.

Concepts were also proposed for displaying IM information on the ND. The standard CDTI symbol for depicting ADS-B Targets was a chevron, and in particular, a green chevron with a shape-hugging border indicated that the Target was coupled to an on-board application. For both concepts, ND conventions for displaying CDTI symbols were implemented, such that the aircraft ID of the Target aircraft was displayed, subject to pilot control. Further, if the ND range selector put the CDTI symbol(s) out of range, convention dictated that a half symbol for the symbol appeared on the outer range ring of the ND at the appropriate bearing.

The first concept displayed the Target aircraft as the green “double” chevrons (left panel of Figure 12). This concept was for displaying the Target aircraft with a minimum of clutter on the ND, and no distinction was made between the two Target aircraft other than their associated IDs. The second concept added a green “selected” circle around the active Target aircraft (right panel of Figure 12). Another enhancement was a data block associated with the selected Target, which always appeared in the lower left portion of the ND and contained information associated with the selected Target aircraft, including the aircraft ID, aircraft type, spacing interval type, spacing deviation and landing runway. This concept was thought to provide significantly more information about the active Target aircraft, at the expense of additional ND clutter.

Note that while the first concept could be considered to be a selectable subset of the second, the ability to select ND views was not available in the study’s scenario presentation, so the concepts were presented separately.

Additionally, two types of spacing conformance indicators were used. Shown in the right panel of Figure 12 is the conformance box, representing the maximum acceptable forward and aft position of the aircraft. This box was range-based (the time-based limits within the IM software was converted to distance), therefore the size of the depicted box varied in accordance with the range selected on the ND. A second type of spacing indicator was used on the left side of the ND during this experiment (not shown), however since it received slightly less favorable ratings than the conformance box, it has been dropped from this research work.

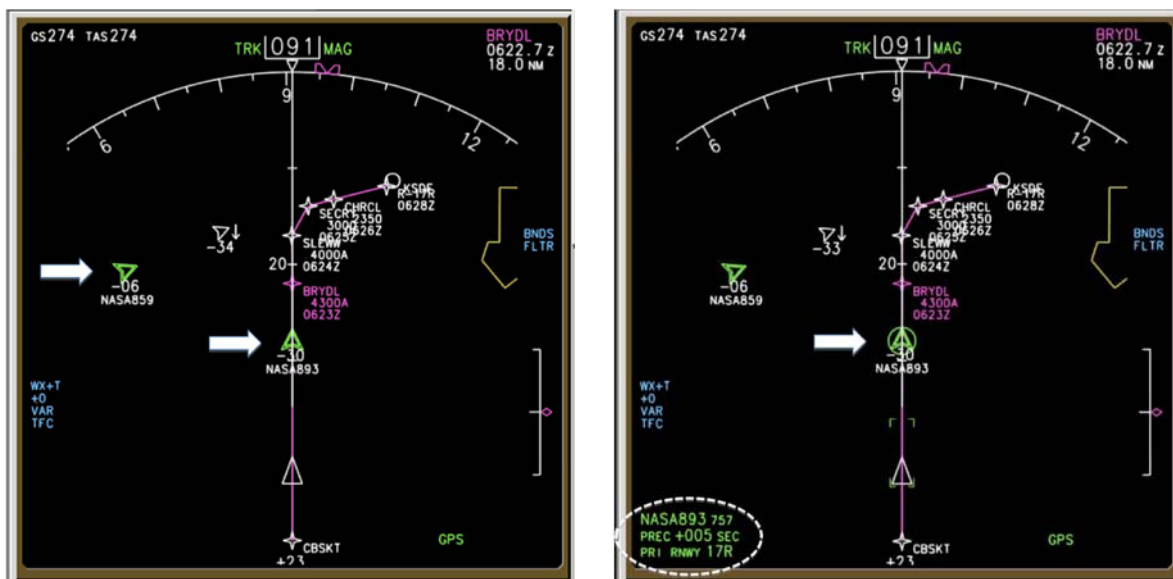


Figure 12. Minimal (left) and enhanced (right) Target data during the interface study.

2.5.2 Procedures

An experiment session consisted of several presentations displayed on a workstation consisting of a computer monitor and a mouse. The associated computer was programmed with the ASTOR software, which simulated the operation of a modern commercial Boeing glass cockpit. Before the experiment began, the subject pilot was given a pre-experiment briefing on the IM operation to parallel runways concept, and the proposed cockpit displays that were to be evaluated.

The bulk of the session consisted of nine runs, each of which presented the subject pilot with a recorded spacing scenario replayed on the ASTOR platform. The experimental runs each simulated an IM spacing operation. At normal speed the recorded simulations would have lasted approximately twenty-four minutes, however the ASTOR playback functionality allowed the speed of playback to be varied by the test operator. This was used to fast-forward the playback through periods of relative inactivity, and each run was shortened to approximately five to seven minutes.

Ideally only one independent variable would change per run in order to best associate its interrelation to the dependent variables. This approach was considered both impractical and unnecessary for this usability study, as it would have taxed the desired 2-3 hour time limit for the experiment, and it was believed the grouping of certain design elements would not significantly compromise the subjective data obtained. The runs were given a run number so they could be correlated to the post-run questionnaire data, and the run order was randomized for each test session to prevent unintended bias introduced by a set order.

Subject pilots were current or former commercial airline pilots, with experience in a modern Boeing glass cockpit. Volunteers were solicited by contacting the United Airlines operations center, and the subject pilots were tested at their domicile.

2.5.3 Results

For the two methods of displaying the IM speed, there was no statistically significant difference between the usability and helpfulness of the speed, indicating the subject pilots had a high degree of confidence in the usability of either design option, with the text option rating slightly higher for all categories. However one subject noted the text is always visible, but sometimes the speed bug is not readily visible (that is, where it was expected to be).

The rating for the usability of Target aircraft characteristics consistently favored the enhanced data block option over the minimal data block option (Figure 12), indicating that pilots found the additional information useful and helpful.

Results also indicated a slight enhancement in the subject pilot's ability to judge the aircraft's spacing progress with a trend indicator, that is, the conformance box. The benign nature of the recorded spacing scenario did not cause significant deviations to be displayed, possibly diminishing the perception of its potential usefulness. Nevertheless, an overwhelming percentage of the subjects preferred the presence of the conformance box as a trend indicator.

Additional subject pilot comments and results from the experiment include:

- Detecting the speed changes is almost as important as displaying the speed itself.
- The relative position from Ownship to Target was rated as very important information.

- Other important information rated as important included the aircraft ID, the spacing deviation, and the spacing interval type.
- All IM related display elements should be removed after the final approach fix to prevent distracting the pilot from landing the aircraft.

2.5.4 Impact

The following observations influenced the design of IM displays used in subsequent research:

- Both textual and graphical presentations of the IM speed are considered useful.
- The spacing trend indication (conformance box) was considered the least important design element, yet was still rated as useful by most subject pilots.
- Sufficient support exists for the refinement of data block information to be investigated.

2.6 IM with Spacing to Parallel Dependent Runways (IMSPiDR)

In 2008, the FAA-led IM working group expressed interest in understanding what impact and benefit IM operations could have for parallel runway operations. Therefore in 2011, NASA LaRC conducted the Interval Management with Spacing to Parallel Dependent Runways (IMSPiDR) experiment, which explored the precise spacing of aircraft during arrival operations to parallel dependent runways (refs. 12 and 13). IMSPiDR used 24 air transport pilots to evaluate the spacing algorithm performance, flight crew performance, and flight crew acceptability of IM procedures during parallel dependent runway operations. The experiment used a 2 by 3 test matrix, consisting of 2 control methods (either a time clearance or an IM clearance) and 3 error sources (no error, wind error, or schedule error). The subject pilots flew one replicate of the no error conditions (time clearance and no error, IM clearance and no error), and two replicates of the remaining conditions, resulting in a total of 10 scenarios flown by each crew.

An eleventh exploratory run was also flown by all the crews at the conclusion of data collection, and it collected only subjective questionnaire data from the crews about alternative displays. This run included the use of a trend indicator, the conformance box, and was identical to the display described in the previous section.

2.6.1 Environment and Simulators

Three simulation platforms were used during the IMSPiDR study to evaluate different levels of aircraft equipage. Some pilots flew the ASTOR simulator, with controls and indications modeled after Boeing 777 cockpit displays (Figure 13). Those pilots flew the ASTOR stations using the auto-pilot fully coupled, the auto-throttles engaged, the MCP speed window closed, and the aircraft in VNAV path mode. The version of the ASTAR algorithm used in this research was integrated into simulation software and made to appear as a part of the FMS, with the IM speed overriding the FMS speed when performing the IM operation (reference 8). Modifications to the ASTAR algorithm included the ability to receive information about two Target aircraft, calculate the time error to both aircraft, and present an IM speed to the crew that achieved the assigned spacing

interval behind one Target aircraft, and simultaneously maintained separation criteria behind both aircraft to meet dependent parallel runway operations.



Figure 13. ASTOR display for IMSPiDR.

Other pilots operated the IFD full-workload simulator (Figure 14) which is a facsimile of a Boeing 757-200 aircraft cockpit that includes standard cockpit instruments representative of a line operations Boeing 757-200 aircraft (Figure 15). The IFD was flown by the flight crew using fully coupled auto-pilot and auto-throttle with the MCP speed window open and the aircraft in VNAV speed mode. The ASTAR algorithm was not integrated into the FMS.



Figure 14. IFD cockpit for IMSPiDR.

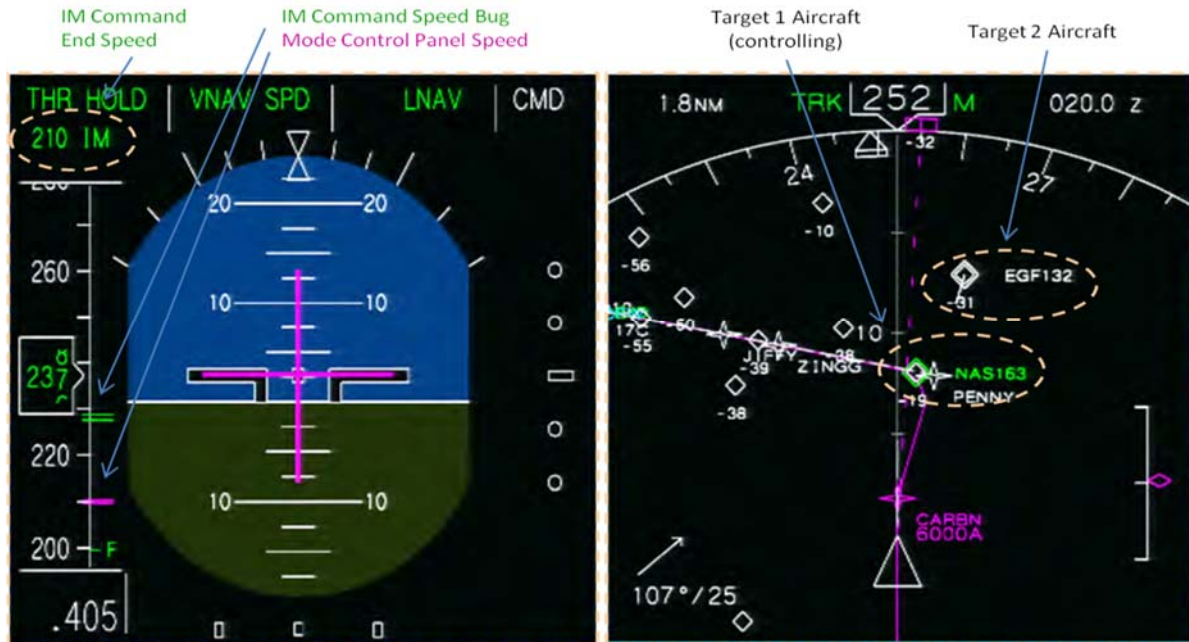


Figure 15. IFD PFD and ND for IMSPiDR.

Some pilots flew the Development and Test Simulator (DTS), a full-scale simulator representative of a current, large, generic commercial transport category aircraft, driven by a high-fidelity aircraft dynamics model (Figure 16). The DTS was flown by the flight crew using fully coupled auto-pilot and auto-throttle with the MCP speed window closed and the aircraft in VNAV path mode.



Figure 16. DTS cockpit for IMSPiDR.

2.6.2 Procedures

The procedures for all three simulation platforms were essentially the same, and a detailed description is available in reference 12. The ASTOR pilot procedures differed from the DTS and IFD pilot procedures in that the ASTOR was operated by one pilot and the other platforms were operated by a crew. Furthermore, the ASTOR pilots used a simulated Boeing 777 CPDLC interface, while the DTS and IFD pilots used the MCDU to conduct CPDLC operations.

The next three figures illustrate what a typical two-Target IM spacing clearance delivered by CPDLC looks like after it is loaded into the FMC and before the “ACTIVATE” button is pushed. Figure 17 illustrates the main IM spacing page and shows the IM achieve by and terminate waypoint (R-17C), the required time of arrival at that waypoint (IM-RTA of 0028:26z), and the identification of the two-Target aircraft (NASA1 and NASA2).



Figure 17. First page of IM clearance via CPDLC on MCDU.

Figure 18 illustrates the information required to conduct spacing with Target aircraft 1, while Figure 19 illustrates the information required for spacing with Target aircraft 2. Both pilots were required to review the information contained on these pages before the spacing clearance was activated (shown at the bottom-right edge of the MCDU in Figure 17).



Figure 18. Second page of IM clearance via CPDLC on MCDU.



Figure 19. Third page of IM clearance via CPDLC on MCDU.

Figure 20 illustrates the main IM spacing page after the IM spacing clearance was activated and both Target aircraft are within ADS-B range. The current IM speed is 0.80 Mach. In this case ASTAR10 is providing speed guidance to the pilots relative to aircraft 1 (NASA1) and is managing an eight second error. In addition, it can be seen that the Ownship will be 3.3 nautical miles behind the aircraft landing on the parallel runway. (Crew interaction with the MCDU for CPDLC and IM was only done in the IFD and DTS.)



Figure 20. MCDU page during IM operation.

Figure 21 illustrates what a two-Target IM clearance looks like when it is uplinked via CPDLC to the ASTOR simulator. It is identical to the clearance uplinked to the IFD which used multiple CDU pages to manage the large CPDLC message. The ASTOR emulated the 777 CPDLC pilot interface, and the crew interaction using the EICAS for CPDLC and IM activities was only done in the ASTOR.

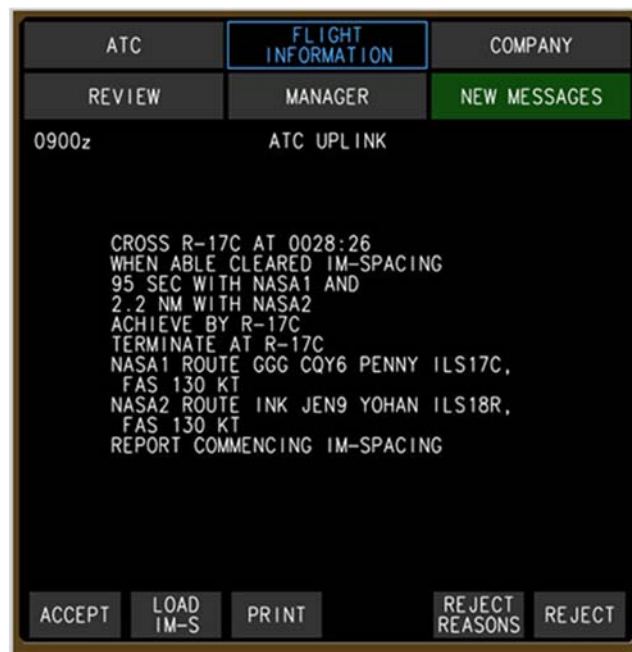


Figure 21. IM clearance via CPDLC on EICAS.

Messages used during IMSPiDR were very similar to previous experiments, expanded to accommodate two aircraft IM spacing operations, and are listed below in Table 1.

Table 1. IM messages used during IMSPiDR

Alert	Message	Meaning	Action
Caution	IM DISENGAGED	Loss of data or internal failure	Terminate spacing procedure
Caution	IM AC 1 OFF PATH IM AC 2 OFF PATH	Target aircraft is not on the expected flight path	Terminate spacing procedure; ATC may issue new clearance
Caution	IM AC 1 ADSB LOST IM AC 2 ADSB LOST	Target aircraft ADS-B information is lost	Terminate spacing procedure
Caution	IM ERROR EXCESS	IM software determines it is not possible to meet the assigned RTA or spacing	Terminate spacing procedure; ATC may issue new clearance
Caution	IM OWN BAD PATH	Flight path provided to IM is invalid or not available	Verify correct information
Caution	IM OWN OFF PATH	Aircraft is outside the set bounds of being ON PATH	Correct to path or update FMC to reflect new path
Caution	IM AC 1 BAD PATH IM AC 2 BAD PATH	No Path or invalid path for that aircraft	Verify correct information
Advisory	IM DRAG REQD	Drag is required to meet IM deceleration rates (> 5 knots between IM speed bug and current airspeed)	Thrust levers to IDLE; Deploy spoilers as required
Advisory	IM SPD LIMITED	Speed is constrained by profile, MMO, or VMO	Advisory only; No action required
Advisory	IM AC 1 SPACING IM AC 2 SPACING	IM has valid data to calculate spacing	Flight crew notifies ATC

2.6.3 Results

Scenarios were flown using either RTA or RTA+IM control methods during various types of error. Results indicate that pilots delivered their aircraft to the runway threshold within 3.5 sec (4 sec standard deviation) of the RTA and within 2.2 sec (3.9 sec standard deviation) of the spacing interval for the respective control methods. Analysis of the time error and number of IM speed changes as a function of position in the arrival stream suggest the spacing algorithm generates

stable behavior in the stream while in the presence of continuous (wind) or impulse (offset) error. The mean time for the flight crew to load the IM clearance into the spacing tool, review the calculated speed, and respond to ATC was under 43 sec.

Pilot reaction time to changes in the IM speed varied by error condition, and it is hypothesized that the no error scenarios had a longer reaction time because the flight crews were less vigilant in monitoring the IM speed than during the wind error scenarios, probably a result of the fewer speed changes. However the 1.6 sec difference in mean reaction time is considered operationally insignificant. The pilot's ability to remain within 5 kt of the IM speed varied by error condition, with the wind error being the most challenging. In-depth analysis indicates the majority of the deviation (in all scenarios) occurred during the initial deceleration to the next IM speed.

Flight crews rated the workload of IM operations as 1.97 (1 very easy, 10 impossible), and the pilot interface used in support of the spacing operation was found to be useful and was used as anticipated. Although the flight crews were able to remain within approximately 6 knots of the IM speed, they reported that the alert designed to notify them of speed command changes was not sufficiently salient, causing them to spend excessive time monitoring the speed command symbology on the PFD.

Pilots reported they moderately agreed it was important to be able to predict the next IM speed change, and moderately agreed that the spacing software itself was predictable. Furthermore, it was determined that some pilots misinterpreted the relationship between the time error value on the MCDU and the speed commands that the spacing algorithm provided. Future displays depicting the time error should concentrate on making this relationship more apparent to the flight crew.

The desire most often expressed by the flight crews was to have a selectable (not always visible) representation of the current status and trend of the IM operation, similar to the "conformance box" used only during the exploratory run, shown in Figure 22. This early variant of the progress indicator (discussed later) provided pilots a snapshot of their time error relative to the maximum acceptable forward and aft bounds. This display was a green box that appeared around the depiction of the Ownship aircraft on the ND indicating how much control authority ASTAR10 has. If the Ownship moved outside the conformance box, the algorithm is predicting that it is no longer possible for the aircraft to meet the spacing goal by a given "achieve-by point." The goal of the conformance box was to provide the flight crew with some predictability whether or not the spacing operation would be successful. Pilots slightly-to-moderately agreed that the conformance box helped them monitor the IM operation and that the conformance box should be part of any display designed to support IM operations. However, the flight crews were only neutral-to-slightly in agreement with the statements that the conformance box helped them predict speed changes, that it increased the level of safety of IM, or that it increased their comfort with IM. And one pilot misinterpreted the conformance box as a separation box, that is, he believed it to display the minimum separation required from the Target aircraft in front of him.



Figure 22. ND with “conformance box” during IMSPiDR.

2.6.4 Impact

The following observations influenced the design of IM displays used in subsequent research:

- Continue to explore alternative methods of depicting spacing time error that are more salient and less prone to misinterpretation.
- The desire most often expressed by the flight crews was to have a selectable (not always visible) representation of the current status and trend of the IM operation (similar to the “conformance box” used during the off-nominal scenario).
- The IM software should limit speed changes that require flap retraction.
- The use of CPDLC is recommended for passing lengthy two-Target IM clearances.

2.7 IM Utilizing Voice and CPDLC (by MITRE)

The IM Voice CPDLC study was conducted in 2013 by MITRE in the Aviation Integration Demonstration and Experimentation for Aeronautics Laboratory, using its en route and flight deck simulation capabilities. The study used controller, flight crew, and pseudo-pilot workstations. The goal of this research was to answer outstanding questions for IM and CPDLC about things such as the validity and acceptability of currently defined IM CPDLC messages as well as their performance parameters and procedures (ref. 14).

2.7.1 Environment and Simulator

The airspace modeled for this simulation was Sector 49 in the Atlanta Center, with some modifications to fit the needs of the simulation (expanded to approximately 80 by 100 miles, and

10,000–24,000 ft). In order to achieve the trajectories needed for the IM operation within the one sector, aircraft flows for arrivals into Hartsfield-Jackson Atlanta International Airport (KATL) were modified to include three flows merging prior to entering terminal airspace. The flight paths of aircraft on the three merging flows were changed slightly from scenario to scenario according to the complexity of IM clearances for that scenario, but the general direction and timing of the flows remained the same. In addition to the arrival flows, some crossing streams were added in order to increase the number of aircraft to a realistic level.

The participant flight crew always flew the KATL arrival and flew through the sector twice during each scenario. After the first run, the flight crew was told by the participant Center controller to contact the Atlanta Approach controller. At this point, they were repositioned as a new aircraft outside of the Atlanta Center simulation sector in order to fly the arrival again. The flow that the participant flight crew followed was alternated among the three arrival flows depending on the scenario.

The flight deck simulator was equipped with two CDTIs that were hosted on auxiliary displays (Figure 23). The CDTI provided basic traffic information to the flight deck, and was used to enter the IM clearance (Figure 24). The IM operation could also be monitored on the ND, and key IM information was proved on the AGD in the pilot's primary FOV (Figure 25).

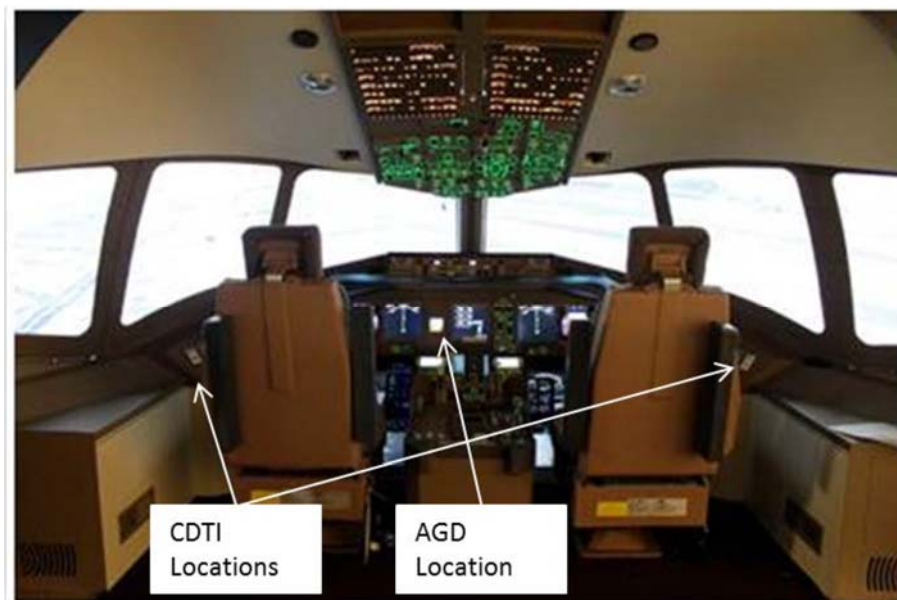


Figure 23. MITRE B-777 simulator IM Voice CPDLC experiment.

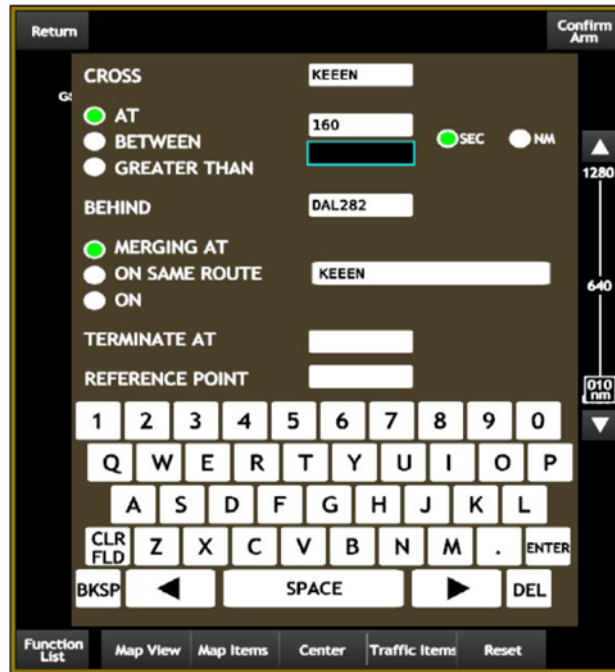


Figure 24. MITRE CDTI for IM data entry.



Figure 25. MITRE CDTI (left) and AGD (right) displaying IM data.

2.7.2 Procedures

During IM operations, controllers decided whether to initiate IM based on automation suggestions. The IM menu contained the IM message along with the relevant interactive buttons from the clearance template for sending messages. For CPDLC-capable aircraft, the controller selected “DATA LINK” in either the clearance template or the IM fly-out menu to send the message. For non-CPDLC-capable aircraft, the controller communicated the clearance via voice and indicated such in the automation by selecting the “VOICE” button.

After receiving an IM clearance from ATC, flight crews accepted the clearance after doing a reasonableness check and then entered the information into the CDTI. After the appropriate requirements were checked and satisfied within the flight deck IM equipment, the first IM speed was presented to the flight crew via the CDTI traffic display and AGD. The flight crew determined whether flying the IM speed was feasible. If it was, the flight crew entered the IM speed into the mode control panel. The same feasibility check and entry of each IM speed was done for each new IM speed until the run was complete or termination was necessary.

The flight crews were instructed that if at any time termination was necessary, they were to press the “DISENGAGE” button on the CDTI. This could be necessary after either receiving a “cancel” IM communication from the controller or determining IM operations were no longer possible. If the flight crew initiated the termination, they were responsible for advising the controller that they were unable to continue IM operations. The flight crew was also instructed that when termination of IM occurs, procedures dictate that they return to their filed speed, unless advised otherwise by the controller.

The responsibilities of the flight crew were divided between the pilots as per normal, current-day operations, with one participant acting as the PF and the other participant acting as PM. The PF was ultimately responsible for all aircraft control actions (e.g., speeds, altitudes) and was instructed to comply with all IM speeds when possible. The PM was responsible for all communications with the controller and for setting up and arming IM.

2.7.3 Results

The majority of pilots and controllers found the integration of the NextGen capabilities of IM and CPDLC acceptable. Controllers seemed to have more difficulty with traffic with a mix of aircraft equipage for IM than they did for a mix of aircraft equipage for CPDLC. Both pilots and controllers found the procedure for accepting an IM clearance to work well for CDPLC. However, some concern was expressed for using the same procedure for voice communications. Both the pilots and the controller preferred CPDLC over voice communications.

Results also indicated that the necessary messages were available for IM as tested, and the CPDLC performance requirements were achieved. CPDLC also reduced the time both controllers and pilots spent on the voice frequency. Overall, pilot and controller responses indicated that the IM clearance was well phrased but that shortening it would improve acceptability.

2.7.4 Impact

The following observations influenced the design of IM displays used in subsequent research:

- The IM clearance was well phrased, but shortening it would improve acceptability.
- Use the preparatory “interval spacing clearance available; advise when ready to copy” when using voice communications for complex IM clearances.
- Determine how to best provide flight crews the necessary information to manage disconnects between the reference aircraft call sign spoken in the voice communication (the airline telephony designator) and the reference aircraft call sign shown on the CDTI traffic display (the airline three letter designator), especially for non-intuitive cases.
- Ensure the Target aircraft trajectory information is kept to a minimum, especially for voice communications (route, waypoints, etc.). IM clearances with 10 or more elements proved challenging in this simulation, and the intended flight path information was often cited as the problematic element.
- Identified the provision of a common progress indication picture between the air and the ground as a potentially important consideration for IM.

3 Overview of Current ATD-1 Research

3.1 IM within the ATD-1 Concept of Operations

The ATD-1 concept of operations combines advanced arrival scheduling, controller decision support tools, and aircraft avionics to enable multiple de-conflicted, efficient arrival streams in high-density terminal airspace. To achieve increased fuel efficiency during periods of high traffic demand, aircraft will use procedures that include a transition from the arrival procedure to the instrument approach procedure of the assigned runway.

The work described in this chapter is different from the previous chapter in that the envisioned time-frame is more near term. Therefore there is no CPDLC available, thereby requiring shorter and simpler IM clearances to be issued via voice, and the aircraft avionics are not integrated, thereby requiring auxiliary devices such as the EFB, AGD, or a configurable graphics display (CGD). The FAA defines the optimal primary field of view as within $\pm 15^\circ$ horizontally of a level line of sight, and within $\pm 15^\circ$ vertically of a 15° downward line of sight. The research reported in this document are for EFBs outside the pilot's primary FOV, and for AGDs and CGDs within the pilot's optimal primary FOV.

IM is designed to support the ATD-1 concept by enabling the en route controller to issue a single strategic clearance to the flight crew to achieve a specific time or distance behind the aircraft it will land behind, called the Target aircraft. The controller is expected to issue this IM clearance prior to the aircraft beginning its descent into the terminal airspace, and that clearance includes the Target aircraft's identifier, the Target aircraft's arrival procedure, and the assigned spacing goal (either in time or distance). Controllers retain responsibility for aircraft separation, and pilots are responsible only for spacing, that is, to fly the IM speed. At any time, the controller can intervene with a speed instruction or a vector, which takes precedence over a FIM generated speed and suspends the FIM operation.

The IM software onboard the aircraft uses Ownship data (route of flight, current location, etc.), and the Target aircraft's transmitted Automatic Dependent Surveillance–Broadcast (ADS-B) state data to calculate the airspeed necessary onboard the IM-equipped aircraft to achieve the IM clearance. To provide predictability as well as stability to subsequent aircraft, the IM speed is limited to 15% faster or slower than the published or standard speed for that segment of the arrival or approach procedure. A detailed description of ASTAR and the spacing software is available in reference 15.

Once the flight crew determines this IM speed is feasible, they notify ATC the IM operation is commencing and fly the IM speed. By flying these speeds, the pilot achieves a precise spacing interval (given by the controller in time or distance) behind the assigned Target aircraft when the aircraft cross the achieve-by waypoint. This achieve-by waypoint can be as early as the point where the two routes merge, to as late as the final approach fix or the runway threshold. The IM operation is complete when the aircraft crosses the achieve-by point, at which point all IM displays are automatically cleared.

3.2 IM for Near-term Operations Validation of Acceptability (IM-NOVA)

The Interval Management for Near-term Operations Validation of Acceptability (IM-NOVA) experiment was conducted in 2012 at NASA LaRC with the goal to assess if the ATM Technology Demonstration-1 (ATD-1) Concept of Operations and procedures, described in ref 1, were acceptable to flight crews in a voice communications environment (refs. 16 and 17). To investigate an integrated arrival solution using air traffic control tools and ADS-B tools, the LaRC IM system, the Traffic Management Advisor with Terminal Metering (TMA-TM), and controller-managed spacing tools developed at the NASA Ames Research Center (ARC) were integrated in the Air Traffic Operations Laboratory.

Data was collected from 10 crews of current, qualified B757/767 pilots who flew the IFD simulator. The simulator was equipped with the ASTAR algorithm and an IM crew interface consisting of electronic flight bags and ADS-B guidance displays. Researchers used pseudo-pilot stations to control 24 simulated aircraft that provided multiple air traffic flows into KDFW, and recently retired air traffic controllers served as confederate center, feeder, final, and tower controllers.

3.2.1 Environment and Simulator

IM clearances were received verbally and entered into the IM system via an EFB. The IM system commanded a speed to meet a scheduled time of arrival (STA) at the IM waypoint, which was the FAF for this experiment. The STA was used until there was valid data for the Target aircraft. At that time the IM-commanded speed was given to achieve the required spacing from that aircraft at the IM waypoint. The assigned spacing interval was set to meet wake vortex and IFR separation criteria. Information about the Target aircraft and the precise time interval to be achieved at the runway threshold are used by the ASTAR algorithm to generate IM speed guidance.

The prototype IM crew interface shown in Figure 26 consisted of two side-mounted electronic flight bags (EFB) and two ADS-B guidance displays (AGDs) mounted under the glare shield in the pilot's forward field of view. The side-mounted EFB was used for data entry and speed conformance monitoring, while the AGDs were used for the presentation of IM-commanded speed and the deviation from that speed.



Figure 26. EFB and AGD for IM-NOVA.

IM speed guidance was only given until the Ownship reached the FAF. At that point the system provided commanded speeds for the aircraft to achieve a stabilized approach speed at 1000 ft AGL. During IM operations, the separation between aircraft was never less than the standard separation criteria used today. ATC was still responsible for separation assurance and could have discontinued the use of IM spacing if separation was a concern.

3.2.2 Procedures

Previous IM research conducted at NASA LaRC utilized datalink to transfer information from ATC to the flight crew. However, during the timeframe ATD-1 will occur, the ground infrastructure necessary to support datalink will not be available to conduct IM operations, therefore voice communications will be relied upon to transfer information necessary for IM operations. In the IM-NOVA experiment, confederate controllers issued IM clearances to the flight crews, who then entered information into the EFBs and activated the IM avionics (shown in Figure 27). The IM procedure required the flight crew to enter the following information included in the IM clearance into the EFBs:

- IM achieve-by point (i.e., FAF)
- Scheduled time of arrival at the IM achieve-by point
- Target aircraft call sign
- Assigned spacing goal (spacing interval required at the IM achieve-by point)
- Target aircraft flight path (arrival and transition)

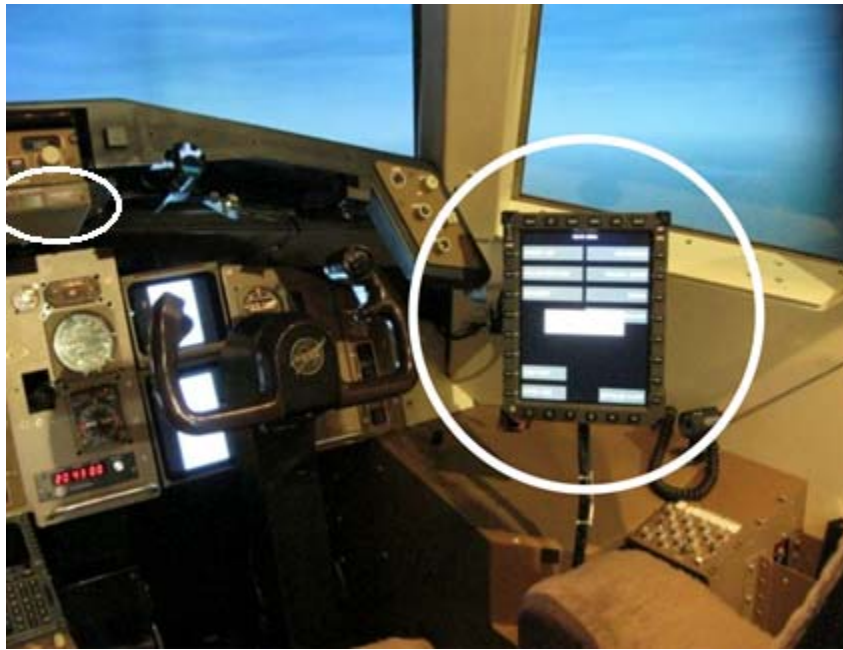


Figure 27. Location of AGD (left) and EFB (right) during IM-NOVA.

3.2.3 Results

Pilot participant feedback indicated that the procedures used by flight crews to receive and execute IM clearances in a voice communications environment were logical, easy to follow, did not contain any missing or extraneous steps, and had an acceptable level of workload. The majority of the pilot participants found the IM concept, in addition to the proposed IM crew procedures, to be acceptable and indicated that the ATD-1 procedures can be successfully executed in a near-term NextGen environment.

Qualitative data obtained from pilot participants indicate that the crew procedures used to receive and execute interval management clearances in a voice communications environment were found to be acceptable, and the workload level was also rated as acceptable. The proposed procedures were found to be logical, easy to follow, and did not contain any missing or extraneous steps.

3.2.4 Impact

During IM-NOVA, pilots voiced a concern that the white IM light on the AGD was small and lacked sufficient saliency to inform crews of changes to the IM-commanded speed. Otherwise no additional comments about the IM logic, messages, or displays were noted.

3.3 Interval Management Speed Awareness and Conformance Experiment (IMSACE)

The Interval Management Speed Awareness And Conformance Experiment (IMSACE) experiment in 2012 evaluated an implementation of IM that was integrated into the PFD and ND, as well as three “retrofit” implementations that could be installed on present day aircraft using an AGD and EFBs (ref. 18). The IMSACE HITL experiment also included the use of oculometers to capture subject pilot eye movement.

The research team evaluated four avionics conditions:

1. Integrated. The IM-commanded speed was presented in the upper left corner of the PFD and speed profile deviation information was implicitly indicated as the deviation between current speed and the IM instantaneous speed (depicted as a bug on the speed tape). In this avionics condition, clearance information would have been entered, and could be referenced, on the IM page of the MCDU. Significant deviations from the speed profile triggered an EICAS message, and the fast/slow speed deviations were present on the IM MCDU page.
2. Aft-mounted EFB. The EFB was used as the device housing the IM algorithm and presented all the relevant information for the operation, including the assigned speed, speed deviation information, and all elements of the IM clearance. Significant deviations from the speed profile triggered messages on the same EFB display.
3. Forward-mounted EFB. The same EFB was placed in a more forward position, immediately below the side window. Displays, messages, and alerts were identical to those used in the aft-mounted condition.
4. Aft-mounted EFB plus AGD. An aft-mounted EFB was augmented with an AGD and mounted under the MCP. The AGD repeated the same IM speed and speed deviation information provided on the EFB.

For this study, the IM clearance was pre-loaded for the pilots prior to each experiment run, and the IM-commanded speeds were scripted to occur at specific points in each experimental run. These IM-commanded speeds began a few minutes after the start of each scenario, which coincided with a few minutes prior to the aircraft initiating descent, and continued until the Ownship reached the FAF.

This study also tested the use of three combinations of visual and aural notification for three events: the onset of a new assigned speed, conformance deviation from the required speed profile, and a reminder if the new speed was not entered. The notification methods used were

- VVV (only visual indications for all three events);
- VAV (visual indications for all three events, plus an aural indication for speed conformance deviations);
- AAA (visual indications and the same aural indication to indicate all three of these events).

The objective of this study was to examine whether these avionics conditions and notification methods affected pilots’ performance, ratings associated with workload, situation and awareness, and opinions on acceptability. The results of this study are in the service of three practical aims: (1) to contribute to the iterative design process and down-select of avionics configuration for future assessment of the ASTAR spacing algorithm at NASA; (2) to provide information useful to the

FAA Human Factors Division (ANG-C1) in their mission to identify issues pertinent to flight certification of, and flight standards for FIM operations; and (3) to identify methodological issues that may be helpful to future FIM human-in-the-loop (HITL) investigations.

3.3.1 Environment and Simulator

Twelve commercial pilot crews (with both pilots from the same airline) flew data collection runs in the IFD, a fixed-base flight simulation environment similar to a Boeing 757-200 (Figure 28). The EFBs can be seen in the picture below outside the pilot seats, and the AGDs are directly underneath the MCP.



Figure 28. IFD cockpit for IMSACE.

Scenarios were from just prior to, or just after, the TOD until landing at KDFW; and contained realistic traffic and communications environment. Crews received IM commanded speeds in the displays previously discussed. Crews were instructed to dial newly commanded speeds into the MCP speed window “in a timely manner.” The aircraft operated in VNAV Speed with the MCP speed window open until the flaps were extended, at which point the autoflight mode reverted to VNAV Path. Crews flew VNAV Path until receiving the final speed to achieve stabilized approach by 1000’ AGL, and all guidance was removed at 1000’ AGL.

Figure 29 illustrates the implementation of IM speed guidance as it was integrated into the PFD. The IM-commanded speed appeared in the upper left corner of the PFD, just above the speed tape. This value was also indicated on the speed tape as a horizontal magenta line. The MCP selected speed was represented on the PFD speed tape as a double green line. When the speed in the MCP speed window matched the IM-commanded speed, the double green line bracketed the magenta line on the speed tape. Figure 29 shows the ND with integrated IM guidance. The Target aircraft was identified by a double green chevron that surrounded it.

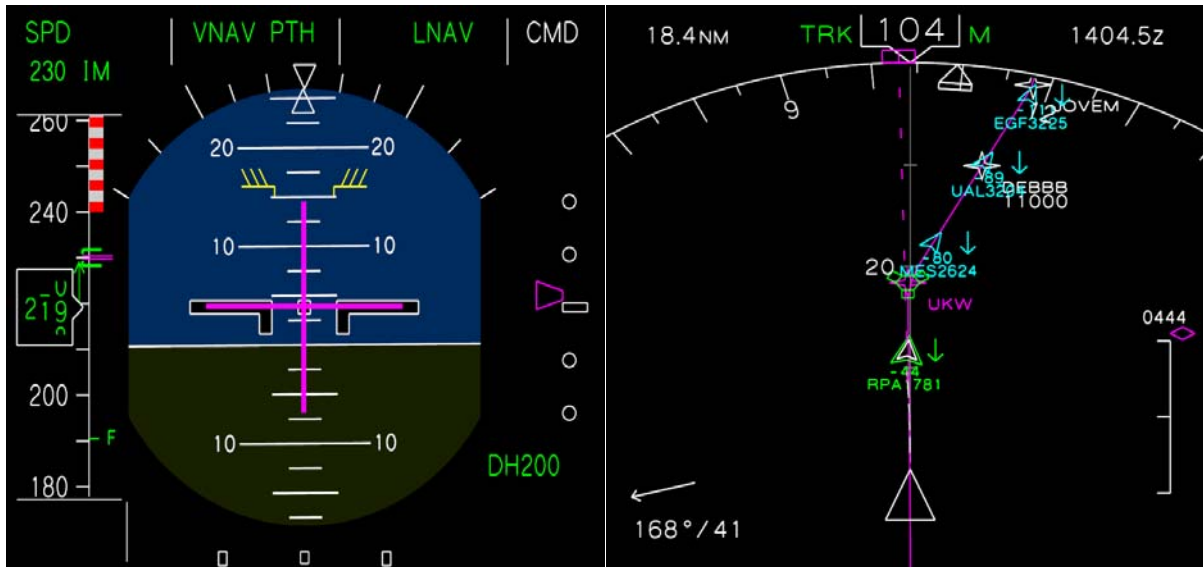


Figure 29. IFD PFD and ND for IMSACE.

The left side of Figure 30 shows the information displayed on the EFB during IMSACE. The Target aircraft was identified by a double chevron in green. Reverse video was used to highlight speed deviations (when the aircraft speed was more than 7 kt off of the IM-commanded speed for more than 12 sec and not converging). A value of 22 kt indicated the aircraft was 22 kt greater than the IM-commanded speed and a value of -22 kt indicated that the aircraft was 22 kt slower than the IM-commanded speed. Reverse video was also used when the speed shown in the MCP speed window did not match the value in the “CMD SPD” window of the EFB for more than 10 sec.

The right side of Figure 30 shows the AGD used during the IMSACE experiment. The white light to the far left of the device would illuminate whenever there was a new IM-commanded speed, and the window below the CMD SPD label displayed that speed. The numbers in the CMD SPD window would blink if after 10 seconds the pilot had not set that speed in the MCP speed window, and would return to steady whenever that specific speed was set. The FAST/SLOW window indicated conformance of the aircraft’s actual airspeed to what the spacing algorithm expected at that time. In this example the aircraft is 9 kt faster than what the ASTAR algorithm expected for that moment in time.

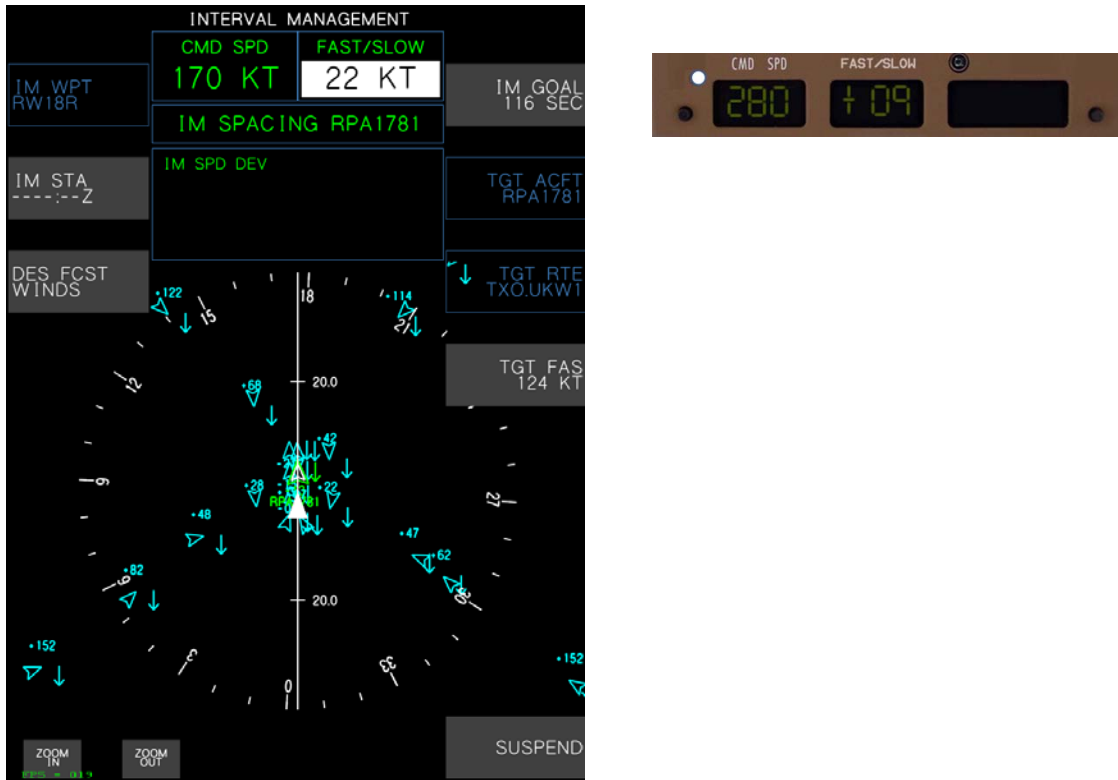


Figure 30. EFB (left) and AGD (right) during IMSACE.

Each crewmember flew using each of the avionics conditions, once as PF and once as PM. Each crew used only one of the notification methods. Four crews experienced each of the three notification methods. Dependent variables included vertical and speed profile deviations, response time to dial in commanded speeds, out-of-speed conformance and reminder indications, post-run questionnaire items (workload, situation awareness, usability, and operational acceptability), and post-experiment questionnaire items that focused more on comparing the avionics conditions.

3.3.2 Procedures

The IFD was hand flown with the auto-throttles engaged (lateral and vertical navigation turned off to increase pilot workload), and airspeed prompts were received from the onboard IM system.

Each experimental run began either at cruise altitude or on descent with both the autopilot and auto-throttles engaged. The forecast descent winds, arrival route, and the instrument approach were programmed into the FMC, using a descent profile of Mach 0.80 and 300 kt. The IM clearance was pre-programmed into either the MCDU or EFB, as applicable. Both lateral navigation (LNAV) and VNAV paths were active at the start of each run. Pilots were provided with the IM clearance from ATC confederates prior to each run, and shortly after simulation start, they were cleared to descend via the arrival. Upon receiving an IM-commanded speed, the crew entered that speed in the MCP speed window. Upon passing TOD, the crew turned off the autopilot. IM-commanded speeds were flown for the arrival, where crews used drag or power to remain within ± 400 ft of the VNAV profile.

3.3.3 Results

Results indicate a clear preference for the integrated solution; however, the most conformance errors occurred when this solution was used without any aural indications. The aft-mounted EFB avionics condition received poor ratings associated with acceptability and the ability to support timely detection of deviations. For the remaining two conditions (forward-mounted EFB and the aft-mounted EFB plus AGD), there was no significant difference in the number of conformance errors, vertical deviations, workload scores, or situation awareness scores. Between these two retrofit solutions, other results seemed to favor the condition in which IM information was presented on the EFB in the forward position, as this condition was associated with less extreme speed excursions, fewer reminders, shorter response times, improved subjective impressions of situation awareness of commanded speeds' onsets, and overall operational acceptability. One result was contrary to this trend: the EFB in the forward position was not considered to be significantly different from the EFB in the aft position with regard to perceived distraction to operations; whereas the EFB in the aft position with the addition of the AGD seemed to improve ratings. Pilots' comments reinforced the results indicated in the ratings: the integrated solution was most preferred, and the EFB in the aft position the least preferred. While generally positive, pilots expressed concerns about the placement of the EFB in the forward position with respect to readability and potential to introduce vertigo. The condition with the AGD also garnered generally positive comments, but pilots mentioned that indications were sometimes overlooked on this display. (Results associated with notification methods impinged on the overall preference order of the remaining conditions.) Pilots who experienced these conditions with aural indications (the AAA method) for all three IM events preferred the EFB in the forward position over the condition with the EFB in the aft position plus the AGD. Pilots who experienced avionics conditions with either the VAV or VVV notification methods rated this later condition higher than the AAA method.

Twenty-two of the 24 pilots in this study recommended an aural indication to convey at least one of the three possible IM events identified; this included all eight of the subjects that did not experience any aural indications (using the VVV method). Most results indicated that pilots who received the AAA notification method were best supported for IM operations. This method was associated with the lowest overall workload scores, perceived better support for detection of speed profile deviations, the fewest number of reminders, and the fastest time to enter speeds in the mode control panel.

The highest number of speed conformance deviations were seen when crews used the Integrated condition, but these were significantly mitigated when paired with a notification method that provided aural indications (VAV or AAA). Using the AAA or VAV notification method when the EFB was in the aft position improved ratings associated with the perceived detection of commanded speeds and reduced the number of speed conformance errors. Without these aural alerts (i.e., the VVV method), this avionics condition resulted in the most extreme speed conformance excursions and lower ratings for situation awareness on other aspects of the flight. Crews using the notification method that only provided visual indications (VVV) showed longer response times on average (about a second than those who had an aural indication for speed deviations, and almost 3 seconds longer for those who had aural indications for all three events), and more excursions from the commanded speed profile. The VAV and VVV notification methods did not differ on the number of reminders crews received, or scores related to workload or frustration; or perceived situation awareness of new speeds, speed deviations, or of the TTF.

The aural indications, thresholds for reminders, and conformance indications used in this study were found to be appropriate. In general, IM as implemented in this study was perceived as having no deleterious effect on workload or crew coordination, and, under some conditions, it was reported to have improved situation awareness of arrival speeds and general conditions during approach and descent.

3.3.4 Impact

The following observations influenced the design of IM displays used in subsequent research:

- The Integrated condition was rated highest, and shows support from objective measures; however, without any aural indications, this resulted in the highest number of speed conformance errors.
- If an Integrated solution is not viable, using the EFB in fore position was the most acceptable and generally most supportive retrofit solution.
- The EFB in the aft position and without the AGD should be avoided. Adding the AGD when the EFB was in the aft position improved the acceptability and performance.
- The use of aural indications for all three IM events (new speed, conformance deviation, reminders), especially in comparison to the condition with no aural indications, was significantly preferred and supported better FIM performance.

3.4 Interface Study for Interval Management (I-SIM)

The Interface Study for Interval Management (I-SIM) in 2013 was a HITL simulation investigating retrofit IM displays (refs. 19 and 20). The retrofit IM displays that were investigated consisted of an EFB interface that flight crews used to enter information into the IM equipment and an auxiliary display that provided pertinent IM information to flight crews in their primary FOV. The I-SIM simulation investigated two different EFB interfaces and two different primary FOV displays.¹

A total of eight flight crews (sixteen current airline pilots) conducted IM operations into the Phoenix Sky Harbor (KPHX) airport, with each crew flying eight scenarios. For each scenario, the EFB interface type and the primary FOV display type were randomly selected. Throughout the experiment confederate controllers used voice communications to provide IM clearances and other clearances to the pilot participants. Within each scenario, each flight crew was expected to enter their aircraft's trajectory intent information prior to top-of-descent, receive an IM clearance and enter the clearance information into the EFB interface, and fly the speeds commanded by the spacing algorithm.

Each scenario in this experiment was split into two flight segments: entering the IM clearance and monitoring the IM operation. To enable the investigation of EFB displays and primary field-of-view displays, these two segments of flight were assumed to be independent from each other, and

¹ Within this experiment, both the EFB and the primary FOV displays were shown in the forward field of view, due to size constraint of the ASTOR simulation platform. As a result, speed guidance information was omitted from the EFB interface to prevent that information from convoluting the primary FOV display acceptability results.

the performance metrics were carefully selected to pertain to only one segment of flight.² Each group of pilots conducted two replicates of four distinct scenarios, with the captain flying one replicate, and the first officer flying the other replicate. Data elements within each display type were held constant throughout the experiment.

There were two independent variables associated with each phase of flight. The independent variables associated with the data entry phase of flight were the previously discussed EFB displays, and whether or not the Target's ADS-B information was available when IM was initiated. The independent variables associated with conducting IM operations were the previously described primary field-of-view displays and the Target aircraft's deviation from its expected speeds. These independent variables will not be discussed further in this document, but interested readers are encouraged to refer to references 19 and 20 for further information.

3.4.1 Environment and Simulator

The I-SIM experiment employed a number of ASTOR desktop aircraft simulators, air traffic control stations, and pseudo pilot stations. All of the pilots in this experiment flew dual crew ASTOR simulators (shown in Figure 31). Each simulator contained a high fidelity six degree of freedom dynamics model and aircraft displays shown on three 27 inch touchscreen monitors (Figure 3). Pilots could interact with the desktop simulators through either a mouse or touchscreen interface, and were asked to use only the touchscreen input when operating the EFB interfaces to more closely simulate real life operations. New pages that were added to the EFB interface enabled pilots to enter information into the IM avionics. Information from the IM avionics was displayed on the EFBs and on two auxiliary IM displays located above the right and left primary flight displays.



Figure 31. ASTOR display for I-SIM.

Two different EFB interfaces were examined in the I-SIM experiment. The first EFB interface, referred to as the menu-entry EFB interface, was designed to be similar to the EFB display used in the IM-NOVA HITL experiment (the left side of Figure 32). The second EFB interface, which was referred to as the multi-entry interface, allowed pilots to enter several pieces of information on a single page (the right side of Figure 32).

² Since the data-entry phase of flight and the monitoring phase of flight were assumed to be independent from each other, interaction effects between the EFB interface and the primary FOV display were not studied in this experiment.

The menu-entry EFB interface was based off of the EFB interface used in the IM-NOVA HITL experiment, but added the ability to enter several additional pieces of information to compensate for communication limits between the IM application and the aircraft. Since Ownship trajectory data may not be available from the flight management system of all aircraft, modifications were made to the interface that enabled pilots to directly enter their aircraft's trajectory intent information into the IM avionics. Additional modifications included the removal of the scheduled time of arrival functionality and the addition of the terminate waypoint field to improve conformance with the minimum operational performance requirements that were in the process of being developed. When using the menu-entry EFB interface, flight crews were expected to enter information that described their aircraft's intended trajectory to the achieve-by point, wind information, and IM clearance information using a series of menu-selection pages and text entry pages. When all necessary data was entered, the ACTIVATE button on the bottom right of the main CDTI page switched from inactive to active. At that time, the other pilot could easily cross-check the information that was entered by selecting either the Ownship data menu or the spacing clearance menu. Once all of the information was crosschecked, pilots pressed the ACTIVATE button to activate the IM algorithm.

The difference between the multi-entry and menu-entry EFB pages was that the multi-entry interface allowed multiple pieces of data to be entered on a single page. To simplify the interface design, most of the selection pages were identical to those used in the menu-entry interface. To enter data into the IM avionics, pilots pressed the INTERVAL SPACING button on the main page, bringing them to a series of three data entry pages. The first page contained entry fields for the Ownship aircraft's trajectory intent information, the second page contained fields for manually entering wind information, and the third page contained fields for entering IM clearance information. Pilots used a keyboard on each data entry page to enter in text and numerical information, and used menu selection pages to select routes and waypoints. To simplify display creation, the selection pages used in the multi-entry EFB interface were identical to the selection pages used in the menu-entry EFB interface. When all required information was entered the ACTIVATE button became selectable, enabling pilots to activate the IM operation.

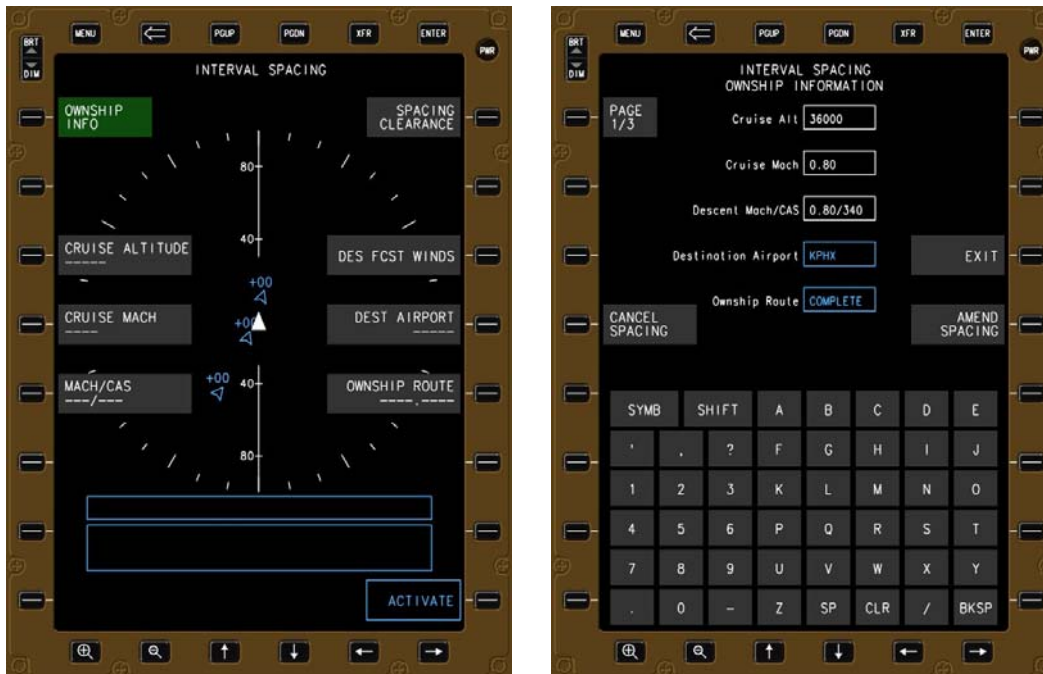


Figure 32. Menu-entry (left) and multi-entry (right) EFB during I-SIM.

There were two primary field-of-view displays that were investigated in the I-SIM experiment. The first primary field of view display option, the AGD, is similar to the primary field of view display was used in several previous IM simulations and flight tests (Figure 33). The second primary field-of-view display option, the configurable graphics display (CGD), was a new display that enabled graphical trend information and text information to be displayed in the primary field-of-view (Figure 34).

The AGD consisted of four main information elements. The left-most number was the IM-commanded speed (feature 1), which is the speed the pilots were required to input into the aircraft's MCP speed window. The middle number was a fast/slow indicator that displayed the difference between the speed expected by the IM algorithm and the aircraft's current speed (feature 2). The right-most number showed the predicted spacing error at the FAF (feature 3). Changes to the IM-commanded speed were indicated by a small green LED light (feature 4).

A caveat for this experiment is that the LED light shown on the ASTOR (emulated on a computer screen) may have been less noticeable than an actual LED light used in the full-scale simulators or aircraft, however the ratings given by the subject pilots in this experiment for LED saliency align closely with results from previous research that used actual hardware.



Figure 33. AGD during I-SIM.

The CGD enabled graphical trend indicators and text data to be displayed in the primary field-of-view. The left-most column of the CGD contained a fast/slow indicator, which displayed the difference between the speed that the spacing algorithm predicted and the aircraft's current speed (feature 1). The middle column displayed the IM-commanded speed (feature 2), the IM mode indicator (feature 3), and the Target aircraft's ID (feature 4). When a new commanded speed was provided, the IM-commanded speed indication switched to reverse video until the flight crew dialed the new commanded speed into the aircraft's MCP speed window. The right-most column contained an IM progress indicator (feature 5), which displayed the IM aircraft's spacing error in relation to estimated feasibility bounds. Within this experiment, the IM feasibility bounds were estimated as $\pm 10\%$ of the time-to-go to the runway threshold. The blank space at the bottom of the CGD contained space for various IM status messages (feature 6).



Figure 34. CGD during I-SIM.

3.4.2 Procedures

Pilots were expected to complete three major tasks during each scenario: enter their aircraft's trajectory intent information into the IM avionics, receive the IM clearance from ATC and enter that information into the IM avionics, and fly the IM-commanded speed to the final approach fix.

At the start of a scenario, each flight crew entered the Ownship trajectory intent information, which consisted of their aircraft's cruise speed, cruise altitude, the speed at which they were expected to transition from Mach to calibrated airspeed, their destination airport, and their aircraft's arrival and approach procedure.

Before the IM aircraft descended below 30,000 feet, confederate air traffic controllers provided each flight crew with an IM clearance. If the IM aircraft and Target aircraft were on the same route, the IM clearance instructed the flight crew to begin IM operations as soon as they were able. When the Target aircraft was on a different route, the IM clearance instructed the flight crew to begin IM operations after they crossed the meter fix. After receiving the IM clearance, the pilots were expected to read the clearance back to air traffic control, enter the clearance data into the IM avionics, and crosscheck the entered data with the other pilot. When IM was activated and speed guidance was displayed, the flight crews were required to verify that the IM commanded speed was safe to fly and then enter it into the MCP speed window. As the commanded speed changed,

the flight crews were required to verify that each new commanded speed was safe to fly and update the speed in the MCP speed window in addition to carrying out their normal tasks. The IM operation ended after the IM aircraft crossed the final approach fix.

3.4.3 Results

In general, the pilot participants found both EFB interfaces acceptable. However, there was a strong preference for the menu-entry EFB interface. The pilot participants stated that they felt that the menu-entry interface was more intuitive and acceptable than the multi-entry interface. The reasons stated for the conclusion were that the multi-entry EFB interface had wind entry fields that did not match the descent forecast winds page on the aircraft's multi-function control unit and the menu-entry interface had less intuitive page navigation.³ Comments from the post-experiment survey and the post-experiment debrief revealed that a majority of pilots thought that the data entry required would be acceptable, but not ideal. One suggestion for significantly reducing the amount of data entry was to require the IM equipment to have the ability to auto-load wind information.

It was also observed that providing pilots with an activation waypoint could result in confusion, regardless of the EFB interface that was used. During the I-SIM simulation, pilots often tried to enter the activation waypoint into the achieve-by waypoint field or terminate waypoint field. For some flight crews, this behavior continued throughout the experiment despite being corrected multiple times. In the future, if the activation waypoint continues to be provided within the IM clearance, this issue could be resolved by adding an activate waypoint field to the interface.

The CGD was found to be more acceptable and intuitive than the numerical AGD, with pilot comments indicating that the main reasons for the difference in acceptability: were the new IM speeds alerts were salient, the graphical information on the CGD was more intuitive than the numerical information on the AGD, and the additional text on the CGD was helpful. In the post-experiment survey, pilots were asked to rate the usefulness of display elements on both the AGD and the CGD (Figure 35). A majority of pilots rated the IM commanded speed indication, the IM mode indicator, and the Target's ID on the CGD as very useful or required for IM. A majority of pilots also rated the usefulness of the fast/slow indicator, the acceleration arrow on the fast/slow indicator, and the IM progress indicator on the CGD as slightly useful to very useful.

The relative ratings of those elements shown on the AGD showed a similar trend. A majority of pilots rated the IM commanded speed as "very useful" to "required" for IM, and a majority of pilots rated the fast/slow indicator on the AGD as not useful at all to moderately useful. The usefulness ratings of the IM commanded speed were lower for the AGD than for the CGD. It is suspected that this difference was caused by a lack of saliency of speed change alerting on the AGD. Based on the results from this study, future auxiliary IM displays should have the capability of displaying text information such as the Target aircraft's ID (feature 4 on the CGD) and the operational state of the IM equipment (feature 3 on the CGD) in the primary FOV.

Within the post experiment debrief, pilots indicated that they found very limited use for the IM progress indicator, and that the saliency of speed change alerting should be increased on both the

³ The wind entry field on the multi-entry EFB required pilots to enter the wind altitude, speed, and direction as a single input. The FMS simulated in this experiment required pilots to enter altitude in one field and the wind speed and direction in a separate field.

graphical AGD and CGD (but particularly on the numerical AGD).⁴ These results are consistent with those of previous experiments. The IMSACE experiment found that aural alerts of new IM-commanded speeds were preferable. Similar to results from the ATAAS and IMSPiDR experiments, the pilot ratings indicated that the IM progress indicator did not create the intended ability to better assess their situation, and in some cases, the indicator caused confusion for the pilots. These results are also consistent with the RAPTOR and IM-NOVA experiments, where IM operations were successfully conducted without any IM progress indicator.

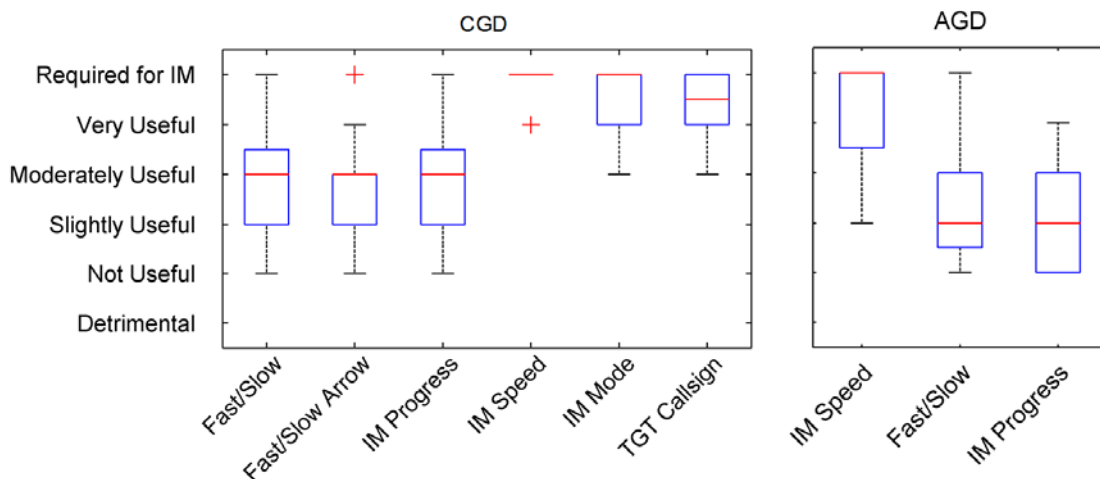


Figure 35: Pilot ratings of the usefulness of IM symbology on the primary FOV display

3.4.4 Impact

The following observations influenced the design of IM displays used in subsequent research:

- The IM application should allow pilots to auto-load the forecast wind information.
- When ATC provides an IM clearance instructing pilots to begin IM operations at a particular waypoint (as opposed to initiating immediately as in most other experiments), the IM display and crew procedures need to be clarified to prevent confusion by the crew.
- Auxiliary IM displays should have the capability of displaying the Target aircraft's ID and the operational state of the IM equipment in the primary FOV.
- For achieve-by operations, the IM progress indicator was rated as the least useful display element (also rated as less useful in previous experiments). The progress indicator should either be redesigned to increase its usefulness, or removed from the primary field-of-view if a more useful indicator cannot be designed.
- The saliency of new speed change alerting should be increased for the retrofit display implementation. This could either be accomplished through an aural chime or a flashing indicator.

⁴ These results are only valid for an achieve-by IM operation.

3.5 Research and Procedural Testing of Routes (RAPTOR)

The Research and Procedural Testing of Routes (RAPTOR) experiment was conducted in 2014 at the NASA Langley Research Center. The objective of RAPTOR was to assess if an update to the ASTAR achieved the ATD-1 Project's requirements for the percentage of controller or pilot interrupted IM operations, as well as the pilot workload and acceptability of IM operations. The specific update to the ASTAR algorithm was the addition of a groundspeed feedback loop, which was to compensate for the Target aircraft having to absorb delay, which translated into it flying slower than the expected speed profile (the speeds on the charted procedure). This delay and resultant slower than expected Target speed was observed in the previous ATD-1 experiments, and causing the IM aircraft to have undesirable closure rates on the Target aircraft.

Four crews of current, qualified 757/767, 777, and 787 commercial airline pilots participated in RAPTOR, with each two-person crew was employed by the same airline and their airline standard operation procedures were used to the maximum extent possible.

A single group of recently retired air traffic controllers served as confederates, actively controlling the aircraft during the experiment. They acted as two Albuquerque center controllers, one Phoenix feeder controller, one Phoenix final controller, and one ghost controller. All controllers were trained at NASA Ames Research Center in the use of all ground-based tools and participated in previous ATD-1 experiments. The Center and ghost controllers rotated positions between runs.

Four pseudo-pilots utilized single-pilot ASTOR stations to operate four human-piloted Target aircraft to support IM operations. Five pseudo-pilots used five MACS pseudo-pilot stations to operate 77 MACS aircraft by responding to controller commands issued via radio communications.

3.5.1 Environment and Simulators

The simulation airspace was arrivals into the Phoenix Sky Harbor International Airport (KPHX), landing to the west, and some modifications were made from the current operational airspace. It contained two Albuquerque ARTCC sectors (Sector 39 and 43), one TRACON feeder position (Apache), and one TRACON final position (Freeway). A transition was added that was manually entered by the aircrew to connect the downwind arrivals to the instrument approach for runway 26. The aircraft started on various arrivals in Albuquerque Center airspace.

One crew flew the IFD, one crew flew the DTS, and two crews flew ASTORs. Every crew flew each scenario twice – once with the captain as PF and the first officer PM, and once with the first officer as the PF and the captain as the PM (each crew flew a total of four experiment runs).

The IM displays consisted of an EFB (Figure 36) and a CGD (Figure 37). The EFB was located on the pilot's outboard side, and was the IM input device (once IM was activated, it was no longer needed and could be used for other functions such as approach charts). The CGD was located in the pilot's forward FOV, and was designed to contain all information necessary to perform IM.

Data entry in the EFB was partitioned into the left side inputs for Ownship information, and the right side for IM clearance information. The Ownship information would be entered any time inflight, and included planned airspeeds, arrival and approach routings, and forecast descent winds. The IM clearance information was entered by the crew after receiving the clearance from ATC. This included the spacing interval, Target aircraft call sign, and Target aircraft's arrival routing.

The two EFBs were configured to cross-talk to each other, so that information could be verified by both pilots.

Once the IM operation was initiated, the EFB and CGD displayed the IM-commanded airspeed, fast slow indications, and IM messages. The EFB also contained a CDTI map that showed all aircraft transmitting ADS-B within reception range, and highlighted the Target aircraft symbol in green. The CDTI was a situational awareness display and was not certified for navigation.

This legend and description refers to the EFB shown in Figure 36.

- 1) CMD SPD: shows the current airspeed the airplane should fly to achieve the spacing goal.
- 2) FAST/SLOW: shows the deviation actual speed is from commanded speed.
- 3) Status box: current IM state (CALCULATING, SPACING BEHIND, and SUSPENDED).
- 4) Alerting box: displays cautions generated by the IM system.
- 5) CDTI: Ownship displayed as a solid white triangle centered in the circle; the Target aircraft is shown as two chevrons with the inner chevron white and the outer green. The Target call sign and altitude is displayed. Other ADS-B equipped aircraft are shown as blue chevrons.
- 6) OWN INFO: pilot enters Ownship information into the IM software.
- 7) NEXT WPT: displays the next waypoint on the arrival or approach; information only and cannot be modified by the flight crew.
- 8) DES FCST WINDS: pilot enters the descent forecast winds (up to 8 altitudes); can be entered manually by the flight crew or uploaded with an ACARS or CPDLC message.
- 9) IM GOAL: pilot enters the ATC assigned spacing goal.
- 10) TGT ACFT: pilot enters the IM Target aircraft.
- 11) TGT RTE: pilot enters the Target aircraft's arrival route, transition, and approach.
- 12) ZOOM IN/OUT: buttons change the range on the situation display of the EFB.



Figure 36. EFB for RAPTOR.

This legend and description refers to the CGD shown in Figure 37.

- 1) FIM SPD: displays the IM-commanded speed. When a speed change occurs, the new speed is highlighted in reverse video for 10 seconds. If the pilot does not respond within 10 seconds, the speed will flash until that new IM speed is set in the MCP.
- 2) Status box: same as EFB status box.
- 3) Target call sign: displays the Target aircraft's identification.
- 4) FAST/SLOW: same as EFB FAST/SLOW.
- 5) Alerting box: same as EFB alerting box.



Figure 37. CGD for RAPTOR.

3.5.2 Procedures

Flight crews initially programmed Ownship information into the EFBs. Once the IM clearance was received, Target aircraft information was entered and IM was activated. Commanded airspeed was flown until the Final Approach Fix where the aircraft was configured for landing at flaps 30. If the controller intervened, the aircrews were instructed to suspend IM and follow controller commands.

3.5.3 Results

Overall, pilots responded that the crew interface was acceptable, and that the EFB and CGD provided the information needed to safely and correctly conduct an IM operation. All of the pilot participants reported that the amount of head down time required to input information from the IM clearance into the EFB was acceptable. In addition, all pilot participants indicated an acceptable level of engagement with the IM automation and understanding of the IM commanded speeds.

3.5.4 Impact

The crew interface consisting of the EFB and CGD used during the RAPTOR HITL experiment was found to be acceptable. These displays provided the information necessary to conduct IM operations and pilots indicated the information was easy to obtain when needed.

4 Summary of Research and Impacts

This section summarizes key finding from experiments described earlier in this document.

4.1 Pilot acceptability rating

Generally both the integrated displays and the retrofit displays configurations (when the EFB was in the forward position) were found to be acceptable. The format of the integrated displays included commanded speed guidance displayed on the PFD, indication of the Target aircraft's position on the ND as well as CDTI, and the ability to load and accept IM clearances using new IM MCDU pages.

The format for the retrofit display configurations were an EFB display that facilitated data entry and provided pilots with a CDTI, and an auxiliary display in the primary FOV that provided pertinent information needed to conduct and monitor the IM operation. I-SIM compared a primary FOV display that could only display numeric values (AGD) with a glass display that contained graphical trend indicators and text data (CGD). The results indicated that that pilot strongly preferred the CGD over the AGD, particularly due to the CGD's ability to saliently display IM speed changes. Pilot reaction time to new IM speeds was quicker when using the CGD compared to the AGD, and therefore the aircraft speed variation from the IM commanded speed was improved. The IMSACE experiment provided the only direct comparison between integrated and retrofit display configurations. Unsurprisingly, the IMSACE experiment found that IM displays that were integrated into current aircraft displays were preferred over the retrofit configurations.

4.2 Pilot workload rating

With the exception of ATAAS, early IM experiments assumed the IM clearance would be provided via a CPDLC message, which would be auto-loaded by the flight crew. Later experiments assumed CPDLC would not be available in the near-term, therefore those experiments required flight crews to manually enter some Ownship and all IM clearance information into an EFB display. The first experiment that investigated retrofit displays, IM-NOVA, only required pilots to enter information from the IM clearance. Pilot ratings suggested that the task of entering data was acceptable. After the IM-NOVA experiment, it was discovered that some aircraft may not have access to Ownship trajectory intent information or wind information due to communication constraints between the aircraft's FMS and the IM application. Thus, data entry fields for the Ownship's trajectory intent information and wind information were added to the two EFB displays evaluated in I-SIM. The data entry task was still found to be acceptable when using both displays; however, pilot comments indicated the amount of information to be entered was very high, resulting in the recommendation that pilots should be given the option to auto-load wind information (the most time consuming data entry task), and that the task should be performed during a low-workload time period (for example, during cruise). In the RAPTOR experiment, the winds were preloaded for the flight crews, which pilots found to be acceptable.

4.3 Notification of change to IM-commanded speed

When conducting IM operations, the primary task of the flight crew is to monitor the IM displays for new speed changes. To aid in this task, many of the IM displays included either a visual alert,

an aural alert, or both alerts, to notify pilots of a new speed change. The over-arching design philosophy was to refrain from using aural alerts and flashing visual alerts, since these may be overly salient and distract pilots from other safety critical tasks. However, results from many of the experiments, especially where direct autothrottle input from the IM algorithm is not used, have shown that more salient alerts of speed changes are needed; particularly when pilots are using retrofit IM displays. During IMSPiDR (integrated displays), pilots were alerted to a change of the IM-commanded speed via a green box that appeared around the new speed for ten seconds after an IM speed change. The pilot participants commented that the green box was not always salient enough to notice new IM-commanded speeds.

All subsequent experiments used retrofit IM display configurations. The I-SIM experiment examined two primary FOV displays: an AGD and a CGD. The AGD used a small green LED light to indicate a new speed change, and the CGD used reverse video. Pilots found the CGD alerting significantly more salient than the AGD, but commented that they both should be improved.

IMSACE examined both visual and aural alerts of new speed commands. The experiment results indicated that pilots overwhelmingly preferred the aural alerts and their performance was generally increased when they received aural alerts. RAPTOR used the same green highlight that was used in the I-SIM experiment (except the highlight flashed if the new speed was not set into the MCP speed window), but no aural alerts were used. The RAPTOR displays and alerting received positive feedback.

4.4 IM operation progress indicator

Pilots and controllers have repeatedly suggested that they would benefit from knowing if the IM aircraft is going to be able to achieve the spacing goal by the achieve by point, prior to initiating the IM operation, and throughout the IM operation, however, thus far it has been challenging to provide an implementation that is intuitive and unambiguous. At long distances from the achieve-by point, the uncertainties in each aircraft's trajectory and ground speed make such a determination unreliable. Furthermore, even when fairly close to the achieve-by point, if the Target aircraft has a large ground speed deviation from the expected speed, the IM aircraft may not be able to recover to achieve the assigned spacing goal by the achieve-by point.

A range of displays have been used to explore how to provide the pilot awareness about the progress of the IM operation (e.g., a graphical depiction of the spacing error, conformance bounds, and the spacing error value itself). Early IM experiments used a "picnic table" display to indicate where the aircraft would be if it was precisely spaced behind the Target aircraft. This was rated as not useful by the pilots, and at times caused pilots to take undesirable actions that were contrary to the IM-commanded speed and procedures in an attempt to place their aircraft's symbol precisely in the picnic table notch. The IMSPiDER experiment provided pilots with the spacing error value on the MCDU during all of the data collection runs, and provided them with a display called the conformance box during a single exploratory scenario. Pilot comments suggested that while the conformance box provided pilots with an easy way to determine how well the spacing operation was proceeding, it did not help them understand the rationale behind the commanded speeds or provide them with a more accurate mental model of the IM operation.

All indications of the spacing error were removed for the IM-NOVA and IMSACE experiments (retrofit display configuration). The I-SIM experiment introduced a new variation of the progress

indicator (a numerical value on the AGD and as a graphical indicator on the CGD); however, comments from pilots indicated that the progress indicator was the least useful of all IM displays, and many pilots commented that they had not used the display.

This data suggests that the IM progress indicator should either be again redesigned to increase its usefulness, or removed from the primary field-of-view during achieve-by operations if there is no useful design. Future experiments will explore using a progress indicator that does not appear until the aircraft is within 30 nautical miles of the achieve-by waypoint, because there is too much uncertainty to provide reliable information to the crew outside of 30 nm. Once the display is visible, it will provide the crew with situation awareness of the progress (or convergence) of the aircraft's current position to the assigned spacing interval behind the Target aircraft.

4.5 Other comments

An infeasibility check should be performed by the spacing software when the IM operation is initiated, and then be continuously performed throughout the operation. Future research will notify the crew whenever the spacing software calculates the spacing interval cannot be achieved by displaying a SPACING ERROR TOO LARGE message and terminating the IM operation.

Some of the subject pilots indicated a desire to tailor the information shown on the CDTI (the Target information, route of flight, merge point, etc.). This document addresses that comment by the use of pilot selectable filters that allow for Ownship and Target information to be added or removed from the auxiliary displays.

Many pilots expressed a strong desire to be able to predict when the next IM-commanded speed change will occur. Providing this capability requires a significant restructuring of the spacing algorithm, and is not addressed in this document.

Some pilots expressed a desire to have awareness of how close the Ownship aircraft was to the minimum separation criteria from the Target aircraft.

In an environment where the controller is provided with recommended IM aircraft pairs from ground automation decision support software, it should be assumed that the automation system only presents to the controller aircraft pairs that are reasonably aligned to conduct an IM operation.

5 Current IM Logic

This section describes the IM algorithm state logic flow. Figure 38 illustrates the logic flow for only the normal operations (in **bold** arrows), and those actions taken by the pilot (small colored arrows). Figure 39 is the same flow diagram but also includes software driven automatic transitions that occur when the IM operation is automatically terminated crossing the terminate waypoint (OFF), or when there is a software or system failure (UNABLE).

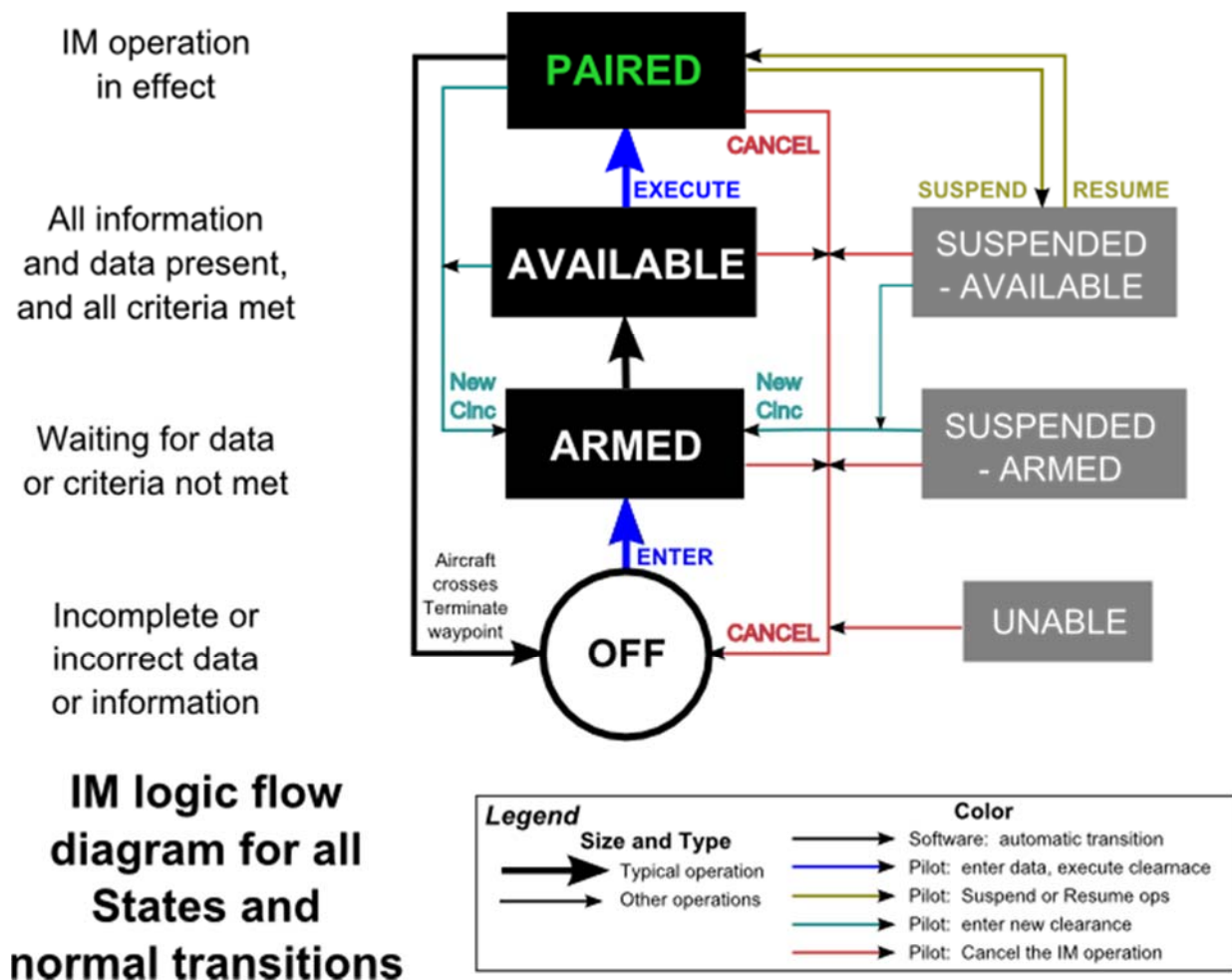


Figure 38. IM logic flow diagram for normal transitions.

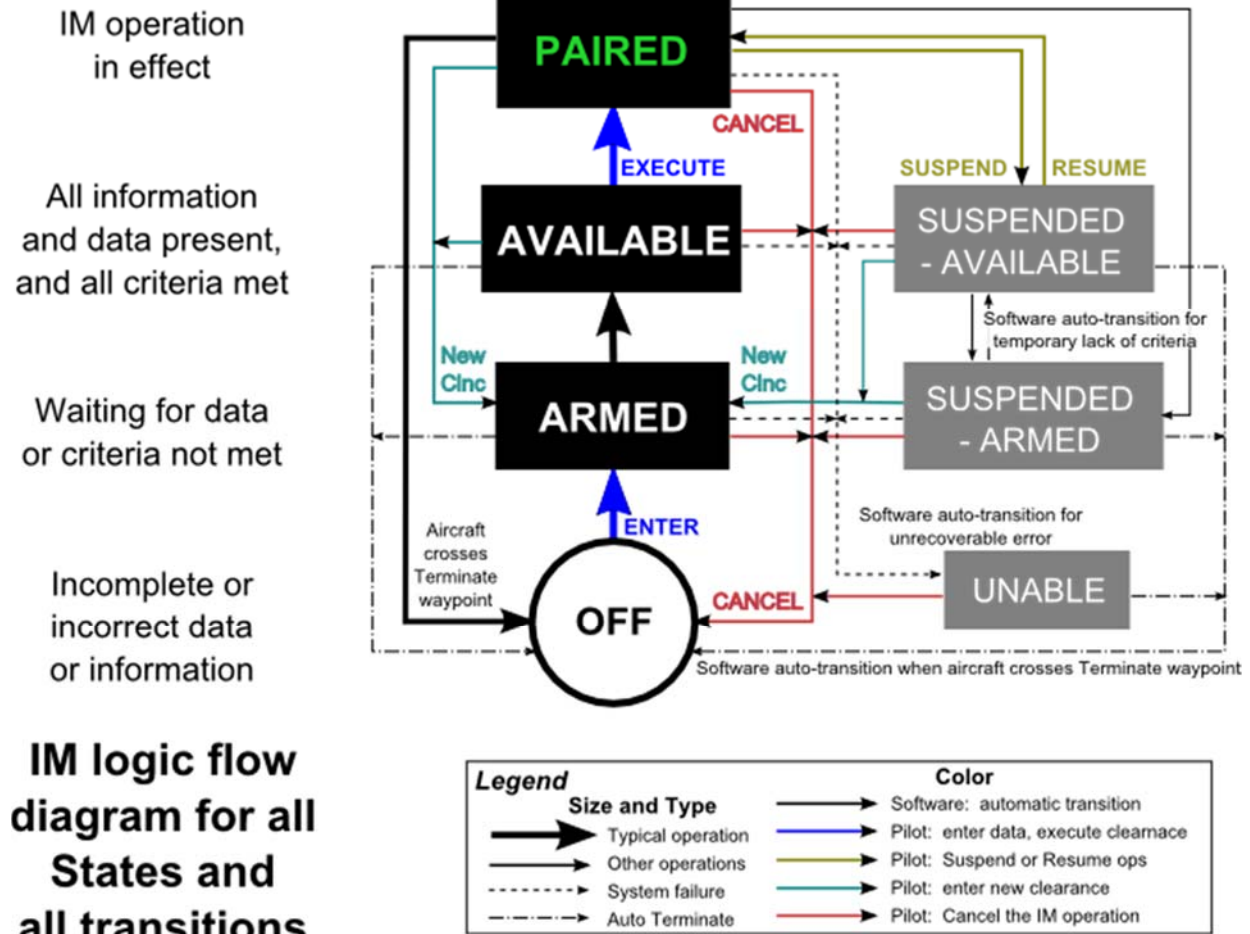


Figure 39. IM logic flow diagram for all transitions.

6 Current IM Clearance Types, Alerting, and Messages

6.1 Clearance Types

Reference 3, paragraph A.3.2.1, lists three of the five IM clearance types (achieve or cross, maintain, and turn), while the remaining two clearance types (final or space, and capture) are derived from a draft version of the follow-on to that document. Reference 3, paragraph A.3.3 and reference 21 provide the basis for the format used by controllers to issue the IM clearances, as described in this section.

6.1.1 Capture

The capture and then maintain clearance type is used when the controller wants the IM aircraft to achieve the spacing goal without identifying an achieve-by waypoint. The advantages of this clearance type are that it allows for the utilization of IM in situations where no achieve-by point is available, and that controller workload should be reduced due to the shorter IM clearance that must be issued via voice communication.

The Ownship and wind information is required if the Target is on a different arrival or approach procedure than the Ownship aircraft, and not required if they are on the same procedure.

Data elements in the IM capture clearance include

- the IM clearance type;
- the assigned spacing goal;
- the Target aircraft identification;
- the Target aircraft routing (optional);
- the IM termination waypoint (optional).

Examples of an IM capture clearance are

- for interval spacing, capture 78 seconds behind DAL3267;
- for interval spacing, capture 78 seconds behind DAL3267 on the EAGUL5 arrival;
- for interval spacing, capture 78 seconds behind DAL3267, terminate at WAZUP;
- for interval spacing, capture 78 seconds behind DAL3267 on the EAGUL5 arrival, terminate at WAZUP.

6.1.2 Cross

The achieve and then maintain clearance type is used when the controller wants the IM aircraft to achieve the spacing goal at an achieve-by waypoint, and then maintain that spacing until the termination waypoint. If the achieve-by and terminate waypoints coincide, there is no maintain phase of the IM operation.

The Ownship and wind information is required if the Target is on a different arrival or approach procedure than the Ownship aircraft, and not required if they are on the same procedure.

Data elements in the IM capture clearance include

- the IM clearance type;
- the achieve-by waypoint;
- the assigned spacing goal;
- the Target aircraft identification;
- the Target aircraft routing (optional);
- the IM termination waypoint (optional).

An example of an IM achieve and maintain (or cross) clearance is

- for interval spacing, cross WAZUP 78 seconds behind DAL3267 on the EAGUL5 arrival, terminate at WAZUP.

6.1.3 Maintain

The maintain clearance type is used when the controller wants the IM aircraft to maintain the current spacing interval (in time or distance), as determined by the IM software. This requires the Ownship and Target aircraft to be on the same route, and the figures in this document show the IM displays auto-populate the Ownship route into the data field for the Target aircraft's route.

The Ownship and wind information is never required since the Ownship and Target aircraft must be on the same arrival and approach procedure.

Data elements in the IM capture clearance include

- the IM clearance type;
- the interval spacing type;
- the Target aircraft identification.

An example of an IM maintain clearance is

- for interval spacing, maintain current time behind ASH2978.

6.1.4 Space

The final (or space) clearance has not yet been fully developed, and will be described in this document similar to the capture clearance type.

Data elements in the IM space clearance include

- the IM clearance type;
- the assigned spacing goal;
- the Target aircraft identification;
- the Target aircraft routing (optional);
- the IM termination waypoint (optional).

The Ownship and wind information is never required since the Ownship and Target aircraft must be on the same arrival and approach procedure.

Examples of an IM space clearance are

- for interval spacing, space 78 seconds behind DAL3267;
- for interval spacing, space 78 seconds behind DAL3267 on the EAGUL5 arrival.

6.1.5 Turn

The turn clearance type is used when the controller wants the IM aircraft to adjust its horizontal path to achieve the assigned spacing goal at the achieve-by point. This concept and procedure is currently outside the scope of this research, and has not been developed or worked on by the NASA research team. However, for completeness, this information is listed here and shown in later illustrations.

The Ownship and wind information is required if the Target is on a different arrival or approach procedure than the Ownship aircraft, and not required if they are on the same procedure.

Data elements in the IM capture clearance include

- the IM clearance type;
- the heading to turn to;
- the achieve-by waypoint;
- the assigned spacing goal;
- the Target aircraft identification;
- the Target aircraft routing (optional);
- the IM termination waypoint (optional).

An example of an IM achieve and maintain (cross) clearance is

- for interval spacing, turn left to 1800, then turn to cross WAZUP at 78 seconds behind DAL3267 on the EAGUL5 arrival.

6.2 Alerts

A structured alert hierarchy was developed for IM displays that aligns with other cockpit display philosophies. IM displays and messages are assigned the lowest possible alert level, then migrate up one level if the pilot does not take action within 10 sec (see table below). No audio alerts or tones are currently used for the IM operation.

Table 2. Alert Levels and Characteristics Used for IM Displays

Alert Level	Criteria	Alert Characteristics			
		Aural	Visual		Tactile
			Display	Color	
3 Warning	Emergency operational or aircraft systems conditions which require immediate corrective or compensatory action by the crew.	ATTENTION or DISCRETE aural alert. Time critical alerts and annunciations may be supplemented by voice message.	Alpha-numeric readout, or icon.	Red	Stick shaker
2 Caution	Abnormal operational or aircraft systems conditions which require immediate crew awareness and subsequent corrective or compensatory crew action.	None	Alpha-numeric readout, or icon. Flashing video used to indicate change > 10 sec ago, but no pilot action has occurred.	Amber (IM speed remains green)	None
1 Advisory	Operational or aircraft systems conditions which require crew awareness and may require crew action.	None	Alpha-numeric readout, or icon. Reverse video display used to indicate change to display until appropriate pilot action is taken.	Optional, but shall be other than red.	None
0 Info	Operational or aircraft systems conditions which require flight deck indication.	None	Discrete lights, alpha-numeric readout, or icon.	Green, Blue or White	None

6.3 Messages

The IM messages displayed on the EFB and CGD are intended to be complete, unique, and succinct. A maximum of 17 characters (including spaces) is desired for the IM message itself to ensure it can be shown on any display device (the MCDU is the limiting device). The messages below are categorized from highest to lowest alert level (caution, then advisory, then info), with no IM messages reaching the criticality of a warning level. Only those messages that enable the pilot to take direct action based on the information in that message are shown in the pilot's primary FOV (Table 3). All other messages (Table 4, Table 5, and Table 6) provide an explanation for the current software state, and are therefore only shown on the EFB outside of the primary FOV. This is appropriate since the pilot takes action based on the IM software state (shown in the primary FOV) and not these messages. Therefore the other messages, regardless of alert level, are only shown on the EFB.

Table 3. IM Caution Messages shown on the EFB and CGD

Message	Criteria	Software State	Pilot Action
AIRCRAFT TOO FAST	This flag is set as true when the aircraft is faster than 0.02 Mach or 10 kt above the IM instantaneous speed for more than 10 seconds.	No change to PAIRED	Reduce throttle and/or deploy speed brake
AIRCRAFT TOO SLOW	This flag is set as true when the aircraft is slower than 0.02 Mach or 10 kt below the IM instantaneous speed for more than 10 seconds.	No change to PAIRED	Increase throttle and/or retract speed brake
IM SPD AVAILABLE	The IM speed available message is displayed when all criteria is met to initiate IM operation. This message is only displayed in the AVAILABLE and SUSPENDED-AVAILABLE states (the IM speed itself will also be visible).	No change to AVAILABLE or SUSPENDED-AVAILABLE	Press EXECUTE or RESUME to initiate IM operation Notify ATC that the aircraft is PAIRED

Table 4. IM Caution Messages shown only on the EFB

Message	Criteria	Software State	Pilot Action
IM SYS FAIL	A failure of the IM software or hardware has occurred, or the Ownship data is not valid.	Triggers UNABLE	Notify ATC unable to initiate or must terminate IM
IM DB NOT CURRENT	Navigation database (DB) used by IM system is not current, therefore IM speed will not be calculated. This check occurs when IM application is initially selected (prior to entry of either Ownship data or IM clearance data).	Triggers UNABLE	Notify ATC unable to initiate IM
OWNSHIP BAD ROUTE	An Ownship bad path is detected as true when there is a valid Ownship traffic record, an Ownship route definition exists, but the calculated trajectory is invalid.	Triggers UNABLE	Notify ATC unable to initiate or must terminate IM
TGT BAD ROUTE	A Target bad route is detected as true when there is a valid Target traffic record, a Target route definition exists, but the calculated trajectory is invalid.	Triggers UNABLE	Notify ATC unable to initiate or must terminate IM
SPC ERROR TOO LRG	The assigned spacing goal or interval cannot be attained by the achieve-by point. This message is triggered when the Infeasibility Flag is true, which is set when the speed required over the remaining route to achieve the spacing interval is greater than 10% above or below the published speed.	Triggers UNABLE	Notify ATC unable to initiate or must terminate IM

Table 5. IM Advisory Messages shown only on the EFB

Message	Criteria	Software State	Pilot Action
OWNSHIP OFF ROUTE	<p>An Ownship off path error is detected as true when there is a valid Ownship traffic record, the Ownship's calculated trajectory is valid, and the data indicates the Ownship has gone beyond any of the various "expected" threshold limits to be on the known path / route. They are:</p> <ul style="list-style-type: none"> • ± 2 nautical miles during straight route segments • 2 nm outside and 4 nm on the inside of turn 	<p>ARMED: no change</p> <p>AVAIL: triggers ARMED</p> <p>PAIRED: triggers SUSPENDED-ARMED</p> <p>SUSPENDED-AVAIL: triggers SUSP-ARMED</p>	<p>ARMED or AVAILABLE: no action</p> <p>PAIRED: inform ATC must suspend IM</p> <p>SUSPEND: no action</p>
TGT OFF ROUTE	<p>A Target off path error is detected as true when there is a valid Target traffic record, the traffic's calculated trajectory is valid, and the data indicates the Target has gone beyond any of the various "expected" threshold limits to be on the known path / route. They are:</p> <ul style="list-style-type: none"> • ± 2 nautical miles during straight route segments • 2 nm outside and 4 nm on the inside of turn • greater than 8000' vertical deviation 	<p>ARMED: no change</p> <p>AVAIL: triggers ARMED</p> <p>PAIRED: triggers SUSPENDED-ARMED</p> <p>SUSPENDED-AVAIL: triggers SUSP-ARMED</p>	<p>ARMED or AVAILABLE: no action</p> <p>PAIRED: inform ATC must suspend IM</p> <p>SUSPEND: no action</p>
TGT DATA LOST	<p>After the presence of a valid ADS-B track file for the Target aircraft, if that track file is subsequently removed (data invalid or no longer received for a longer time period than the Air Traffic Computer allows), the TGT DATA LOST flag is set. If the track file becomes valid again, the message is removed and the IM state changes to SUSPENDED-AVAILABLE.</p>	<p>Triggers SUSPENDED-ARMED</p>	<p>Inform ATC must suspend IM</p>

Table 6. IM Informational Messages shown only on the EFB

Message	Criteria	Software State	Pilot Action
WAITING OWN WPT	The waiting Ownship waypoint message is displayed when the Ownship aircraft is on the specified route, however has not yet passed a speed constrained waypoint.	No change to ARMED	No action
WAITING TGT WPT	The waiting Target waypoint message is displayed when a valid Target track file exists and the Target aircraft is on its specified route, however the aircraft has not yet passed a speed-constrained waypoint.	No change to ARMED	No action
WAITING TGT DATA	The waiting Target data message is displayed when the no Target data flag is set, which occurs when there has never been ADS-B data received for that aircraft. (This message is different from the TGT DATA LOST message in that IM guidance has not previously occurred.)	No change to ARMED	No action
MANUALLY SUSPENDED	Indicates the IM operation was manually suspended by the pilot. This message is retained until the pilot either resumes or terminates the IM operation, that is, the message is still displayed even if the software state changes to Suspended-Armed state (for example, the Target aircraft is off its route).	SUSPENDED- AVAILABLE or SUSPENDED-ARMED	No action
IM SPEED LIMITED	The IM speed limited message is displayed when the IM software calculated speed is being limited by one of the criteria below: <ul style="list-style-type: none">• regulatory (i.e., 250 knots or less < 10,000')• airframe (Mmo, Vmo, maximum speed for flap setting)• > 15% difference from the published speed for that segment	No change to PAIRED	No action

7 Current IM Displays

This section provides high-level descriptions and illustrations of each IM state. The illustrations of the EFB in this document are approximately one-third the size of the actual device (10.4" x 8.0" actual), and the CGD is approximately half the size of the actual device (2.0" x 3.0" actual). The CGD is a repeater of the upper-right portion of the EFB, with the exception of the EARLY/LATE indicator, which is removed due to the small size of the CGD. More detailed information about the displays and logic is provided in Appendix A.

A design philosophy is to auto-populate information expected to be available to the IM application in a retrofit installation. For example, when entering the Ownship information, the destination airport is automatically filled in by the IM software since that data is readily available on one of the aircraft's data buses, but the route information is not since it is not available.

A second design philosophy is to only display data fields relevant to that particular procedure. Therefore when the pilot selects the particular IM clearance type, only the subset of data specified in the ASPA-FIM (ref. 3) and MOPS (ref. 4) is displayed.

A third design philosophy is for the IM software to only display feasible options for the required data fields. For example, once the pilot has selected the Target's arrival procedure, the only approach procedures displayed as selectable options would be those that connect that arrival procedure to the Ownship's landing runway.

7.1 OFF State

The OFF state occurs

- prior to the spacing software's transition to the ARMED state;
- after the automatic termination of the IM operation by the software (e.g., once the aircraft crosses the terminate point or a hardware fault occurs);
- after manual termination by the flight crew (e.g., in response to ATC instructions).

In this state, the EFB either contains no information (which occurs prior to entering Ownship data and shown in Figure 40), or shows the Ownship information if it has been entered (which occurs either prior to entering IM clearance information, or when the IM operation has been automatically or manually terminated, as shown in Figure 42).

All of the pilot interaction with the IM software occurs on either the "Ownship & Wind" page or the "IM clearance" page, while the "IM home page" is used during the IM operation itself.

Pressing the "Ownship & Wind" bezel button or soft-key at the upper-left of the EFB causes the Ownship page to be displayed (Figure 41, left panel). After all the information has been entered, a green "ENTER" button appears at the bottom-right of the EFB (Figure 41, right panel). Pressing "ENTER" transfers the data to the spacing software and returns the display to the IM home page, but this time with the Ownship information visible (Figure 42).

Alternatively (and not shown as an example in this document), the IM clearance information could be entered first by the pilot. In this case, the green ARM button would still become visible after all IM clearance information is entered if Ownship information is not required (e.g., the SPACE and MAINTAIN clearance types), or becomes a green ENTER button if Ownship data is required (e.g., the CAPTURE, CROSS, and TURN clearance types).

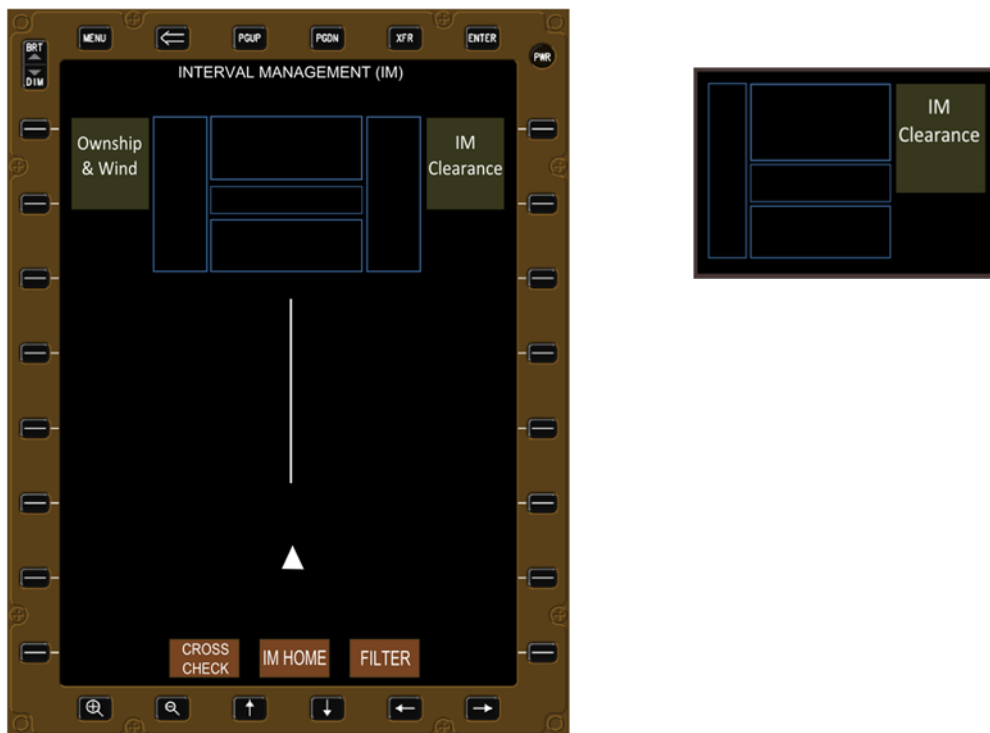


Figure 40. IM home page prior to data entry (OFF).

ALT	HEADING	SPEED	TEMP
300	340	095	-44
240	300	046	-32
180	020	031	-21
100	040	027	-4
SFC	060	012	15

Figure 41. Ownship page without (left) and with (right) information entered.

Pressing the “IM clearance” bezel button or soft-key (Figure 42) causes the IM clearance type page to be displayed (Figure 43). This page allows the pilot to select the IM clearance type, based on the phraseology the controller uses rather than the formal name of the clearance type, which is usually but not always the same. For example, the word CROSS is the phraseology used by air traffic control to issue an ACHIEVE AND MAINTAIN clearance type, therefore the word CROSS is displayed on the EFB and CGD.

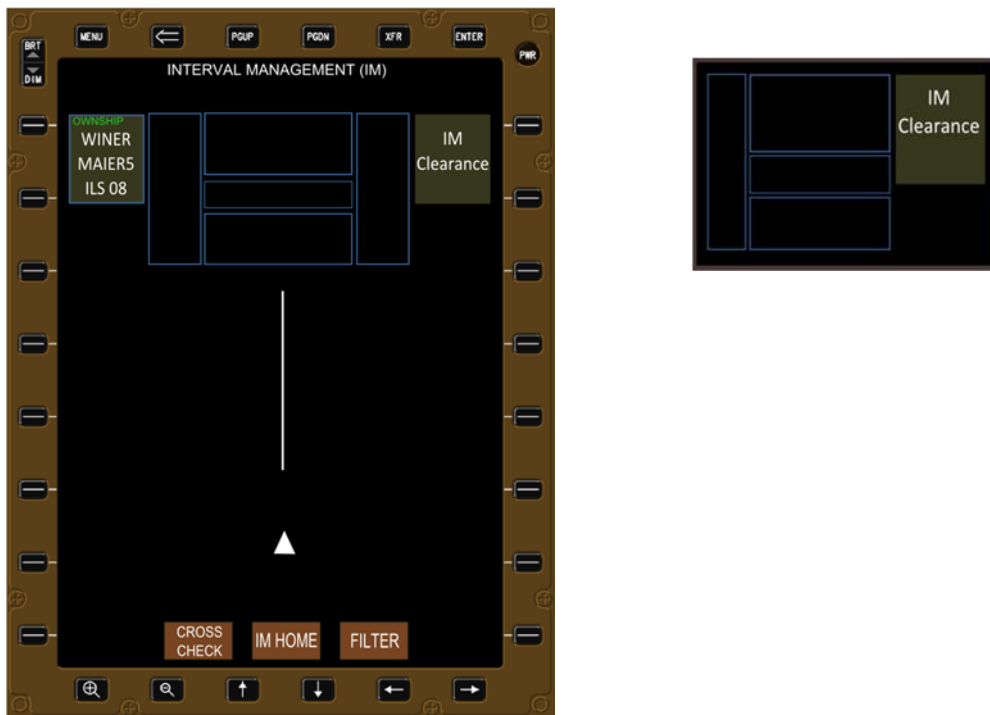


Figure 42. IM home page after Ownship data entry or IM termination (OFF).

After the pilot presses the bezel button or soft-key for the appropriate IM clearance type, the display then shows all the data elements required for that clearance type, listed from top to bottom in the order that the controller is expected to issue that information (Figure 44). This section uses a CROSS clearance type (the achieve and maintain operation) in this section, and an example of a MAINTAIN clearance is shown in Appendix B.

The software automatically selects the next data field (shown by lighter shade of grey, with the box outlined in white). This also can be manually overridden by the flight crew, for example, the flight crew could enter the Target ID prior to entering the assigned spacing goal.

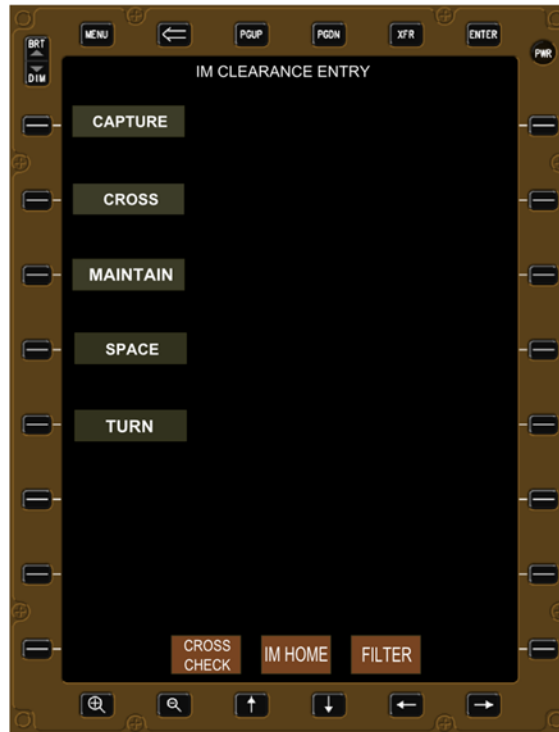


Figure 43. IM clearance type page.

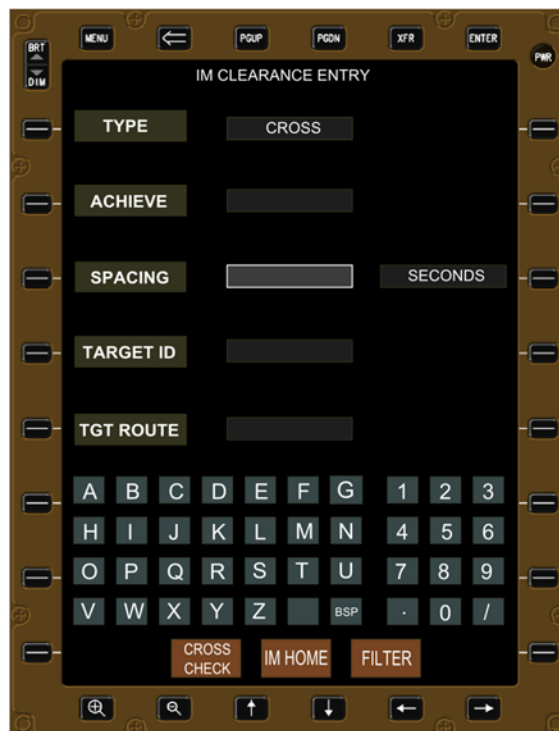


Figure 44. IM clearance CROSS page without information (OFF).

Once all information has been entered, the green “ARM” button at the bottom-right of the EFB appears, indicating all required information has been entered (Figure 45). Pressing “ENTER” causes the IM state to transition to either ARMED (successful data entry, shown later in Figure 46) or UNABLE (invalid data entered, shown later in Figure 51).

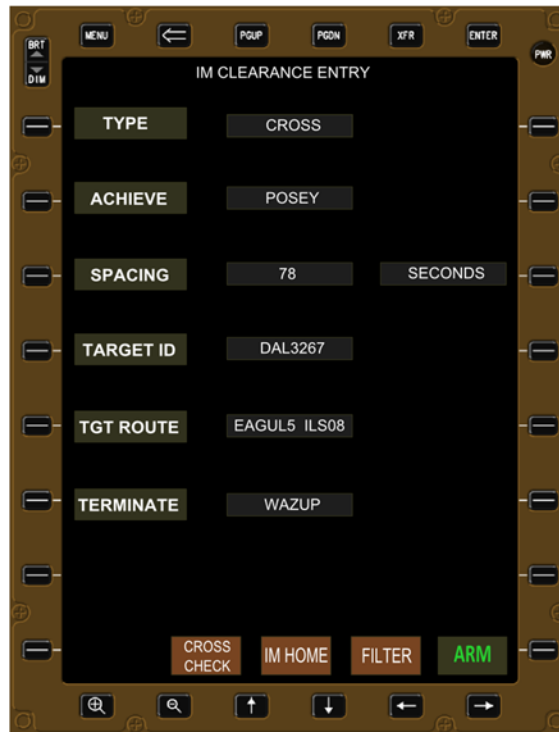


Figure 45. IM clearance CROSS page with information (OFF).

Actions that occur when bezel buttons or soft-keys are pressed include the following:

- Bezel buttons across top and bottom of EFB:
 - MENU: return to top index page
 - Back Key: returns to previous page, all data retained
 - PGUP & PGDN: change pages containing list of data
 - ENTER: same as ENTER soft-key at bottom-right of EFB
 - +and -: zoom in and out
 - arrows: cursor control as back-up to touch screen
- Bezel buttons or soft-keys down left side of EFB:
 - TYPE: new page, displays 5 options
 - ACHIEVE: new page, list of points common to own and Target routes
 - SPACING: activates the spacing field
 - TARGET ID: new page, contains list of valid ADS-B aircraft
 - TGT ROUTE: new page, contains arrival and approach procedure

- TERMINATE: new page, list of waypoints common to own and Target routes
- Bezel buttons or soft-keys down right side of EFB:
 - SECONDS: change to MILES (to SECONDS if already MILES)
- Soft-keys on bottom of EFB:
 - CANCEL (left most position): transition to CONFIRM CANCEL page (Figure 52)
 - Always present after Ownship information is entered
 - Removes IM clearance information; Ownship information is retained
 - CROSS CHECK (right of CANCEL): causes specific IM page to appear on opposite EFB
 - No bezel button associated with this soft-key
 - IM home (center button): causes the IM home page to be displayed
 - Shown in cyan if already on IM home page (i.e. no action available)
 - No bezel button associated with this soft-key
 - FILTER: causes the flight crew selectable filters to be displayed
 - No bezel button associated with this soft-key
 - ENTER (right most button): indicates Ownship or IM clearance data is complete
 - Only visible when all Ownship or all IM clearance data is entered
 - Shares position with “ARM,” “EXECUTE,” “SUSPEND,” and “RESUME”
 - ARM (right most button): indicates all Ownship and IM clearance information is entered
 - PM expected to brief the PF at this point
 - Pressing “ARM” causes software to transition to ARMED state
 - EXECUTE (right most button): all criteria to conduct IM has been satisfied
 - Pressing “EXECUTE” causes transition from AVAILABLE to PAIRED
 - The IM speed displayed on CGD and EFB in large green text
 - SUSPEND (right most button): manually suspends the IM operation
 - Causes transition from PAIRED state to the SUSPENDED–AVAILABLE state
 - All Ownship and IM clearance data is retained
 - The IM speed is removed from the CGD, and changed to small white text on EFB
 - The “SUSPEND” button is replaced with a “RESUME” button
 - RESUME (right most button): manually resumes the IM operation
 - Causes transition from SUSPEND–AVAILABLE to PAIRED state
 - The “RESUME” button is replaced with a” SUSPEND” button

7.2 ARMED State

The ARMED state occurs

- after the flight crew has pressed the “ARM” button;
- the IM software has sufficient and correct information entered by the pilot;
- not all criteria have been met for the software to calculate a valid IM speed.

The EFB displays all the Ownship and IM clearance information entered in the left and right text boxes, and any criteria not met to transition to the AVAILABLE state is displayed in the lower center text box (messages listed in Table 3, Table 4, Table 5, and Table 6). Figure 46 illustrates an EFB and CGD in the ARMED state.

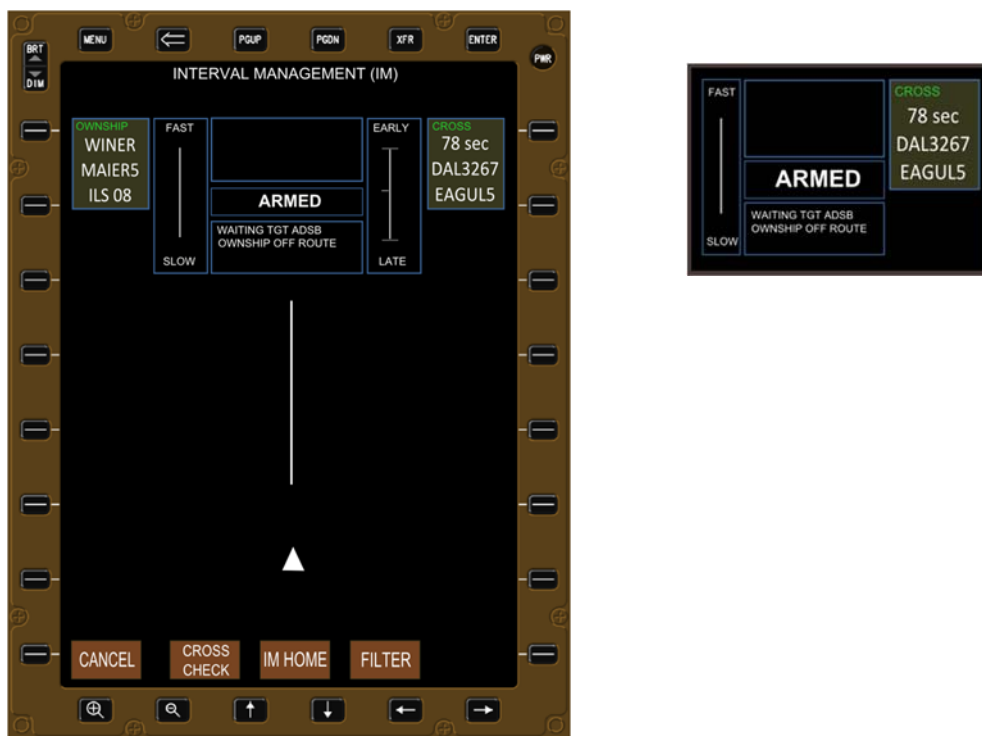


Figure 46. IM waiting for Target aircraft information (ARMED).

There is no required action by the flight crew in this state. The software automatically transitions to either the AVAILABLE state (valid IM speed calculated, Figure 50), the UNABLE state (bad route information, trajectory not feasible based on forecast descent wind, or equipment failure, Figure 51), or the OFF state (aircraft crosses the terminate point or manually cancelled by the crew, Figure 42).

7.3 AVAILABLE State

The AVAILABLE state occurs

- when the spacing software can calculate an IM speed;
- the pilot has not yet pressed the “EXECUTE” button.

The criteria for the spacing software to calculate a valid IM speed are as follows:

- the Ownship is on the specified route
- the Ownship is proceeding to a waypoint with a speed constraint, or has already passed a waypoint with a speed constraint
- the Target aircraft’s ADS-B signal has been received and a valid track file exists
- the Target aircraft is on the specified route
- the Target aircraft is at or has passed a waypoint on that route with a speed constraint

The EFB and CGD show all the information entered, as well as the IM speed to be flown (Figure 47). If the pilot does not press the “EXECUTE” button within 10 sec of it appearing, the “AVAILABLE” text will flash in reverse video after 10 sec on both the EFB and CGD until the pilot presses the “EXECUTE” button at the bottom-right of the EFB. If available, the Target information (bearing, range, altitude, and ground speed) is shown in white on the right of both displays, immediately below the IM clearance box.

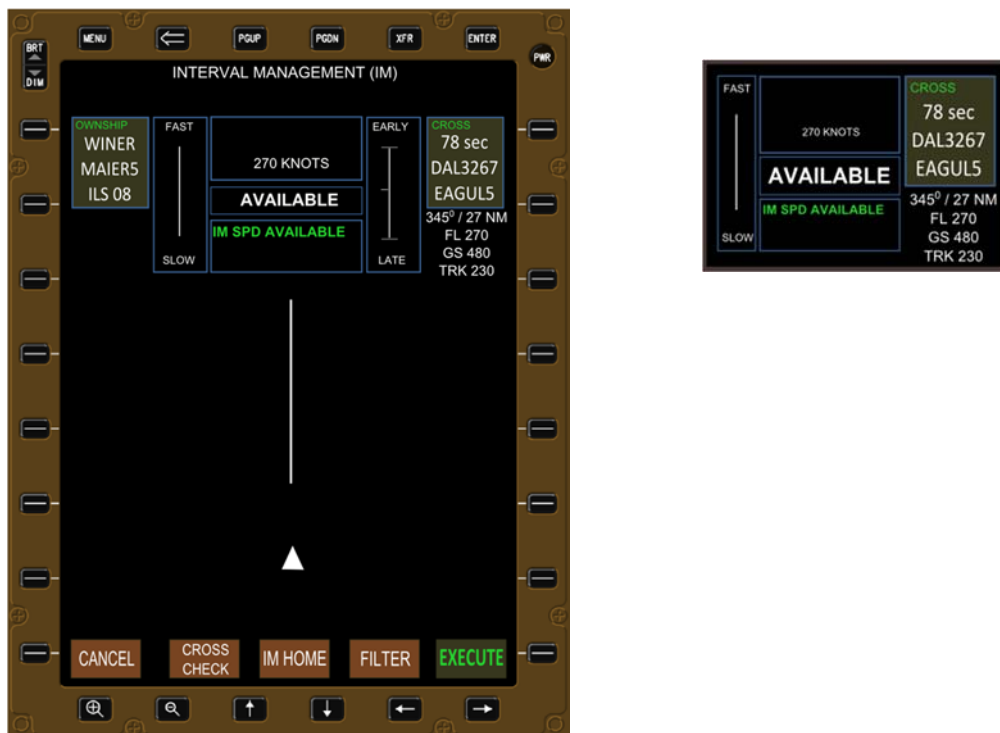


Figure 47. IM operation can commence (AVAILABLE).

The only required flight crew data entry is to press the “EXECUTE” button on the EFB to transition to the PAIRED state. The crew also has the option to press the “CANCEL” button at the bottom-left of the EFB. The software will also automatically transition to the OFF state when the aircraft crosses the terminate point, or transition to the UNABLE state if there is bad route information or software failure.

7.4 PAIRED State

The PAIRED state occurs

- when all criteria to conduct IM are met;
- after the flight crew presses the “EXECUTE” button.

The EFB and CGD display the entered information for the Ownship and IM clearance, the IM speed and state, and the Target information selected by the pilot via the filter section (Figure 48). Changes to the IM speed will be presented in steady reverse video for the first 10 sec on both the EFB and CGD, then in flashing video until the flight crew enters that speed into the MCP speed window. An “IM SPEED NOT SET” message is also shown as soon as the IM speed changes until the pilot sets that speed in the MCP.

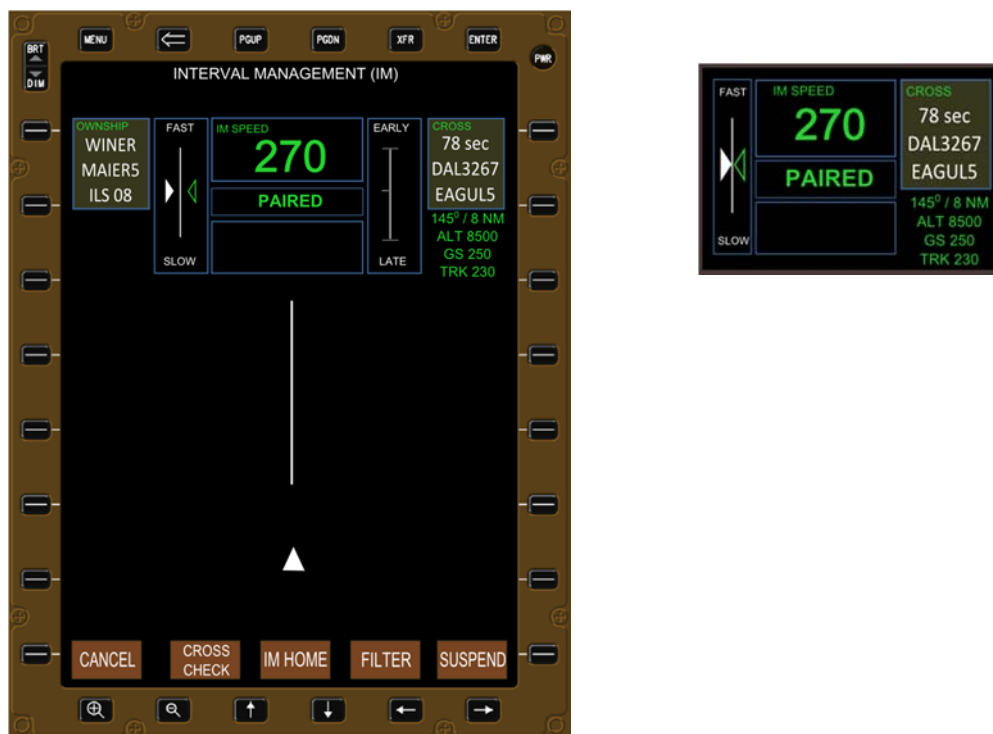


Figure 48. IM operation in progress (PAIRED)

Pressing the “CANCEL” soft-key or bezel button causes a transition to the “CONFIRM CANCEL IM CLEARANCE” page (shown later in Figure 52). Pressing the “SUSPEND” soft-key or bezel button at the bottom-right of the EFB causes the IM software to transition to the SUSPENDED–AVAILABLE state (Figure 50).

The software will transition to the ARMED state when the Ownship or IM clearance information is modified (exceptions are changing the spacing goal or executing a “direct to” in which case the software state remains unchanged).

The software will also automatically transition to the OFF state when the aircraft crosses the achieve-by point, or to the UNABLE state if there is bad route information or software failure (Figure 40).

7.5 SUSPENDED–ARMED State

The SUSPENDED–ARMED state occurs when

- the Ownship is 2.5 nautical miles or greater laterally off the specified arrival route;
- the Target is 2.5 nautical miles or greater laterally off the specified arrival route;
- the Target ADS-B data is lost, and the traffic file is no longer valid;
- the spacing error is too large to be resolved along the remaining route.

The software automatically transitions to the SUSPENDED–ARMED state (Figure 49) when the Ownship or Target aircraft is greater than 2.5 nautical miles laterally off the specified course, the Target ADS-B data is lost and the track file is invalid, or the spacing error becomes too large to resolve. A message is also displayed indicating the cause. When all of the conditions are resolved, the spacing software will automatically transition to the SUSPENDED–AVAILABLE state (Figure 50).

The EFB and CGD retain all information entered, however the IM speed is removed from the speed box, and a message describing the cause for the transition to the SUSPENDED–ARMED state is shown (Figure 49). The IM state and Target information is displayed in white.

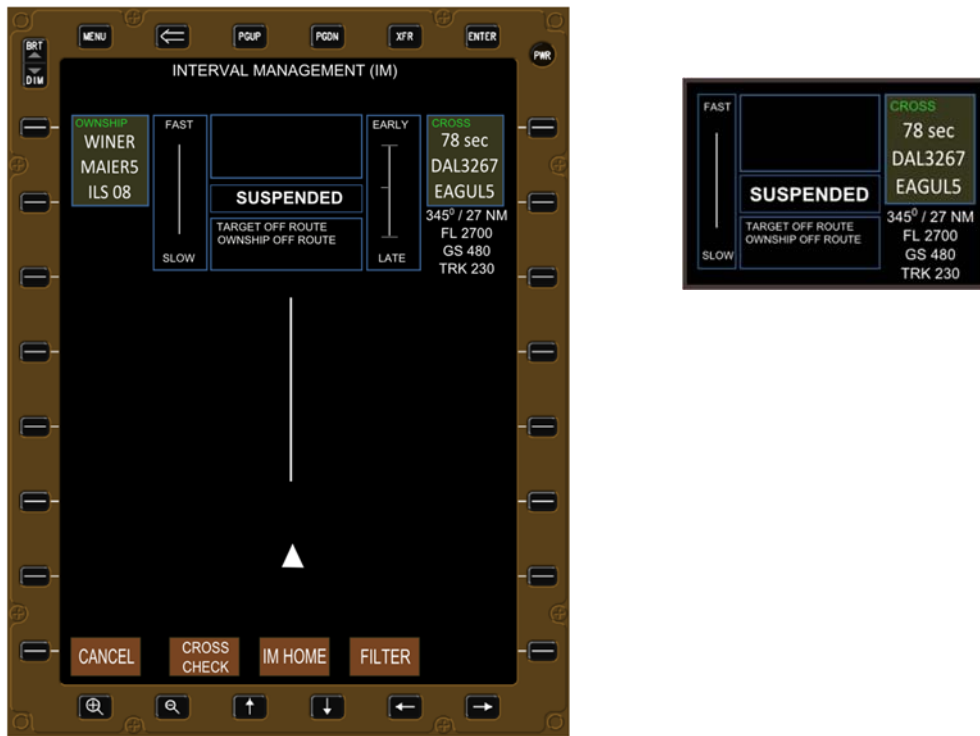


Figure 49. IM operation not available (SUSPENDED-ARMED).

The software can be manually transitioned by the pilots to the OFF state (the “CANCEL” button at the bottom-left of the EFB) or manually to the ARMED state by modifying any of the Ownship or IM clearance information. (The two exceptions are a change to the assigned spacing goal and a change of the next waypoint of the Ownship route, also known as a “direct to” change. In these cases, the software remains in its current mode, and, if in the PAIRED mode, the IM speed is removed and “COMPUTING SPEED” message is displayed until the new IM speed is available. When available, the spacing software automatically removes the message and displays the IM speed.)

The software will automatically transition to the SUSPENDED-AVAILABLE state when all the IM spacing criteria is met again. It will also automatically transition to the OFF state when the aircraft crosses the achieve-by point, or the UNABLE state if there is bad route information or software failure.

7.6 SUSPENDED–AVAILABLE State

The SUSPENDED–AVAILABLE state occurs when

- the IM operation has been manually suspended by the pilot and all criteria are still met to conduct the IM operation (from PAIRED to SUSPENDED–AVAILABLE);
- the criteria that previously triggered automatic suspension of the operation by the software has now been resolved (from SUSPENDED–ARMED to SUSPENDED–AVAILABLE).

The IM state and the Target information are displayed in white (Figure 50). The “RESUME” button is now visible at the bottom right of the EFB (and this is the only state in which it is visible).

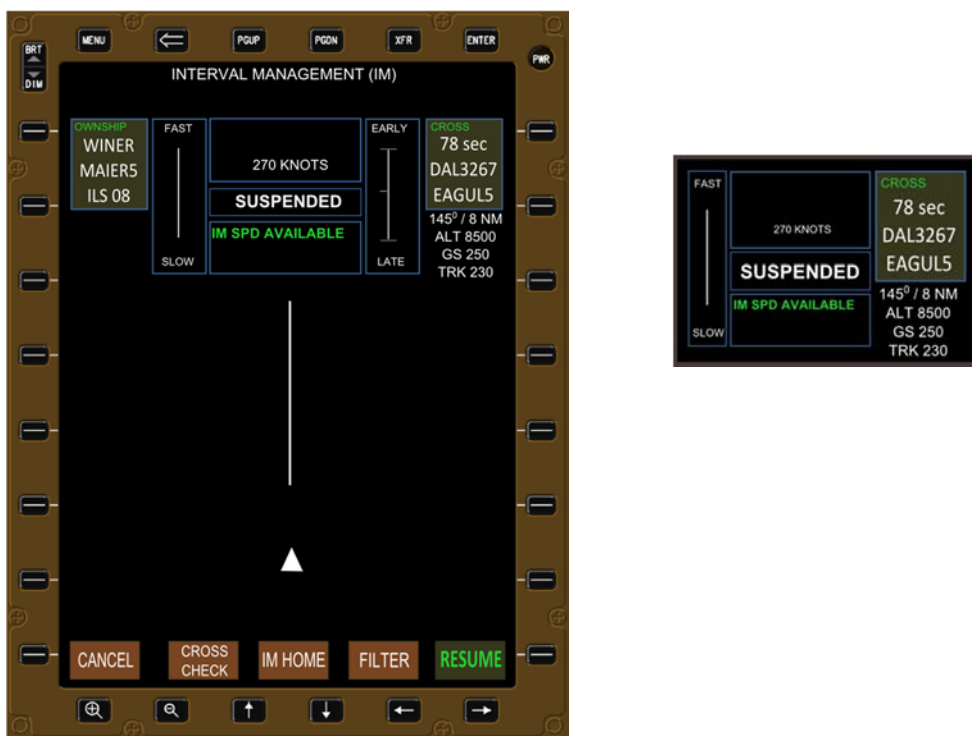


Figure 50. IM operation not in progress but available (SUSPENDED–AVAILABLE).

7.7 UNABLE State

The UNABLE state occurs when

- the IM software is not able to calculate a trajectory for either the Ownship or the Target aircraft (invalid route structure, forecast descent wind causes extreme trajectory, etc.);
- there has been an internal failure of the IM software or hardware.

The only pilot options in this state are to press the “CANCEL” button in the lower left of the EFB, or to update the Ownship or IM clearance data (Figure 51).

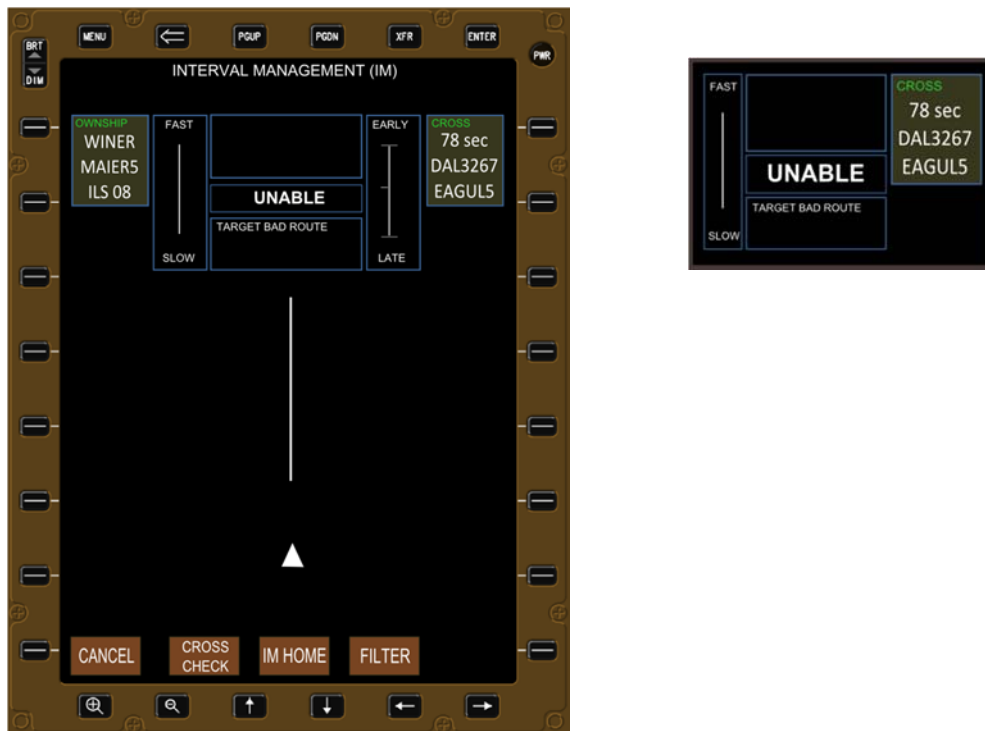


Figure 51. IM operation not possible (UNABLE).

7.8 Confirm Cancel IM Operation

When the pilot presses the “CANCEL” bezel button or soft-key, the IM software display removes all the graphics in the center of the EFB (Target icon, traffic routes, etc.), and displays a “CONFIRM CANCEL IM CLEARANCE” message towards the bottom of the EFB. The “YES–CANCEL” bezel button and soft-key is on the opposite side of the EFB from the previous “CANCEL” button to prevent accidental termination of the IM operation.

Pressing the “YES–CANCEL” bezel button or soft-key terminates the IM operation, removes all IM clearance information, but retains all the Ownship information (Figure 42). Pressing the “NO–CONTINUE” bezel button or soft-key returns the IM display to whatever the previous page was (Figure 52 is an example of the “CANCEL” button originally pressed when in the SUSPENDED–AVAILABLE state).



Figure 52. Confirm cancel IM clearance page.

7.9 Pilot Selectable Filters

The IM software allows the pilot to use filters to tailor what information is displayed on the EFB and CGD. The FILTER page (Figure 53) can be accessed from any other page by pressing FILTER at the bottom of the EFB. After selecting the desired filters, pressing RETURN at the bottom of the filter page returns the display to the previous page with the appropriate information either displayed or not.

This filter methodology is modeled after aircraft avionics currently in commercial service. The software displays developed for pilot selectable filters as part of the NASA research will most likely resemble the route and transition select buttons shown earlier (they turn green to indicate when selected), and not the orange squares shown in this figure.

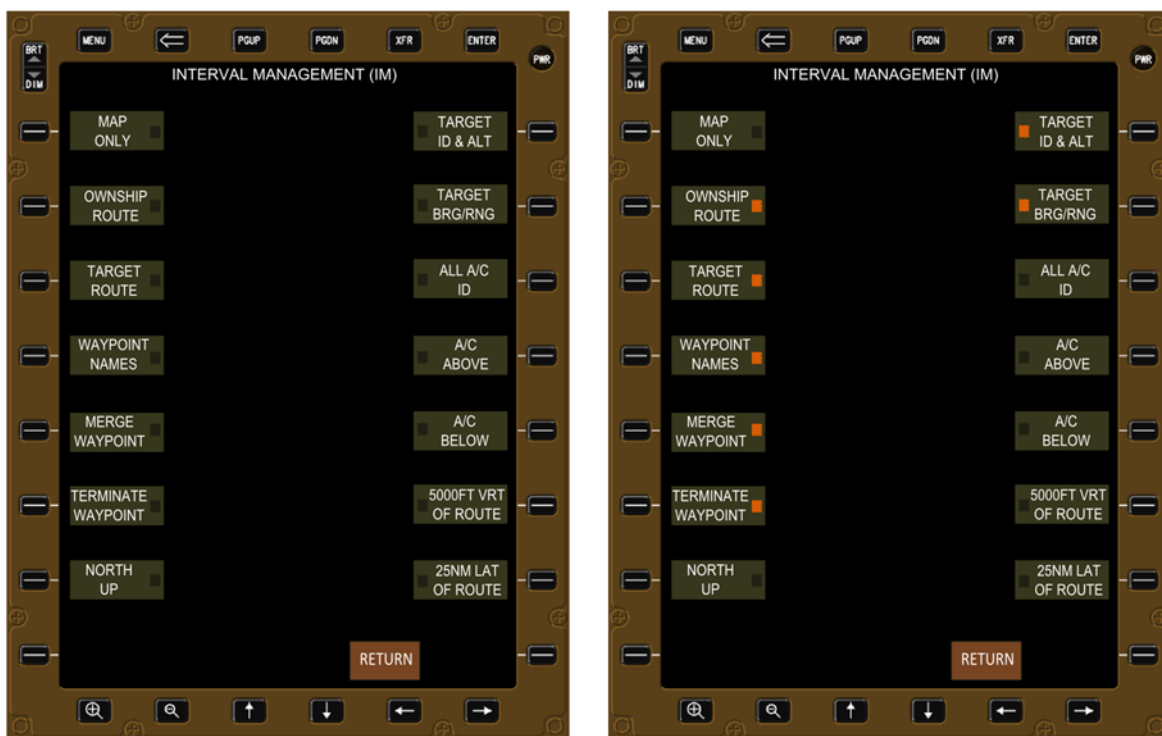


Figure 53. Examples of pilot-selectable filters turned OFF (left) and ON (right).

8 Conclusion

Interval Management is a new aircraft operation being developed, and requires cockpit displays to allow the flight crew to enter information given by the controller into the onboard software. This information has changed over time, and extensive research has provided significant pilot feedback, which when combined necessitated a redesign of the cockpit software and displays. The design criteria used to create the new displays was heavily influenced by industry standards (in particular, the DOT/FAA/TC-13/44 document), and the research team's goal of providing the pilots with all the necessary information while minimizing the workload associated with conducting the IM operation.

Highlights of the IM software and display redesign include

- software states and algorithm logic simplified, and aligned in parallel for operations prior to and after commencing the IM operation
- unambiguous messages that accurately describe event or condition
- some data elements removed from required entry (e.g., Ownship airspeed)
- all data elements that must be entered are shown when a page is selected
- data element entry is linear, progressing from top-left to bottom-left
- data entry requires at most one page off
- words used in the display align with either the next software state (e.g., ARM), or phraseology used between controllers and pilots (e.g., PAIRED)
- pilot selectable filters were added to enable the display to be tailored to the operation

The display to provide the pilots with situational awareness (e.g., the “picnic table” in AMSTAR, the “conformance box” in IMSPiDR, and the “EARLY/LATE” progress indicator in I-SIM) continues to be a challenge. Specifically, pilots have tended to over-control the aircraft (excessive throttle movement resulting in extra fuel burn), second-guess or “help” the algorithm by making larger speed changes than called for by the IM software (again extra fuel burn), or misinterpreting the display as an indicator of separation from the preceding aircraft (which it is not). Development work continues, and results will be published as soon as available.

The other issue that requires more research is the use of aural tones for alerting. A key research objective of the IMSACE experiment was the use of aural indications, which the pilots overwhelmingly reported as acceptable and desirable for detection of IM-commanded speed changes, and reduction of speed conformance errors.

As a result of the redesign, the IM displays now meet the specifications listed in the RTCA document (with the possible exception of the progress indicator and the aural alerting), and the issues identified during previous research have been predominately addressed. The new IM logic, messages, and displays will be used in upcoming IM research at NASA Langley and Ames Research Centers.

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Appendix A Detailed Description of IM States

A.1 OFF State

A.1.1 General Description

The IM system initiates or transitions to the OFF state whenever

- the pilot manually selects the IM application but prior to transitioning to the ARMED state;
- the IM operation is automatically terminated by the software (for example, crossing the achieve-by point or a hardware fault occurs);
- the flight crew manually terminates the IM operation (for example, an ATC instruction).

ASTAR algorithm:

- The algorithm has not been called.

Displays:

- The display may contain no data (when the application is first called; see Figure 40).
- The display may have Ownship data (after entry complete; see Figure 42).
- The CGD is a repeat of the upper-right portion of the EFB, except the “EARLY/LATE” indicator has been removed due to size limitations of the CGD.
- Soft-keys have an associated bezel button (except for “CROSS CHECK,” “IM HOME,” and “FILTER” at the bottom of the EFB), and the pilot may push either to trigger action;
- Text boxes shown in light grey and outlined in white indicate the next expected data to be entered.
- Text boxes shown in dark grey (with or without text in it) can be selected using either the bezel button or the soft-key.
- Text fields that must have data entered via a keyboard include the Ownship airport, the clearance spacing goal, and forecast wind information.
- The Target ID may be entered via the select menu (if the aircraft is within ADS-B range) or via keyboard.

Messages:

- There are no messages in this state.

Alerts:

- There are no alerts in this state.

NOTE: the following are not shown in the figures of this document but will be visible in the actual display:

- compass arc with headings
- aircraft traffic
- the Target aircraft outlined in white (ARMED, SUSPEND, and UNABLE) or green (AVAILABLE and PAIRED)

A.1.2 Entering “OWNSHIP & WIND” Information

Pressing the “Ownship & Wind” soft-key or bezel button (Figure A-1) causes the EFB to present the display shown in Figure A-2. The Ownship and wind information is required if the Target is on a different arrival or approach procedure than the Ownship aircraft, and not required if they are on the same procedure. Therefore the CAPTURE and CROSS clearance types may or may not require Ownship and wind information, whereas the MAINTAIN and SPACE clearance types will never require Ownship and wind information. The TURN clearance type is not currently part of the NASA research domain, and has not been implemented a.

Selecting the “CROSS CHECK” soft-key causes the particular page to be displayed on the opposite EFB, the “IM HOME” soft-key returns the display to the IM home page, and the “FILTER” soft-key causes the page that allows the pilot to select what information is displayed to appear.

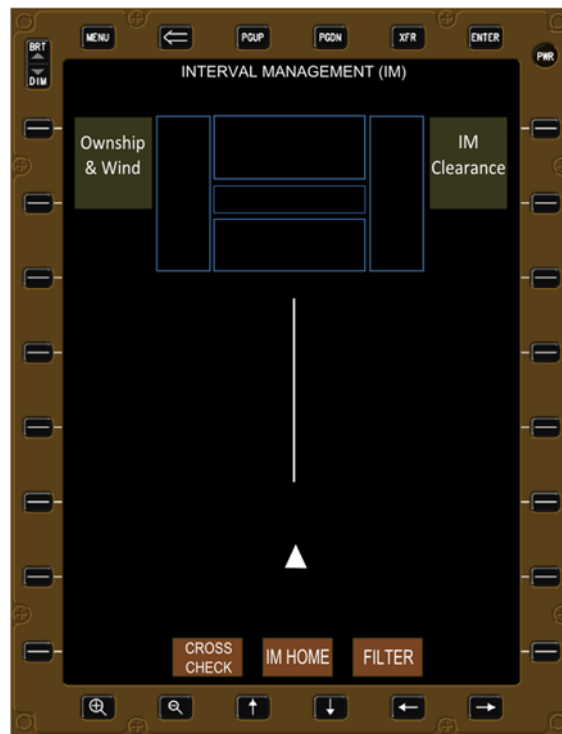


Figure A-1. IM home page with no data entered.

All soft-keys align with a bezel button so that an alternative selection method is available if the touch-screen feature should become inoperative (except for the “CROSS CHECK,” “IM HOME,” and “FILTER” soft-keys at the bottom of the EFB).

Whenever possible, data is auto-populated by the IM software. The IM software also automatically activates the next data field that would typically have information entered (shown in Figure A-2 as light grey and outlined in white).

The IM displays are also designed to indicate when data has not been entered, either by an empty data field, or in the unique case of the wind, it states NO DATA. When data has been entered, it is either visible in the data field, or in the case of the forecast descent wind, it indicates the time stamp of the message used to provide that information.

The Ownship home page shows all information that the pilot must enter, in a logical flow from top to bottom, to enable an IM operation:

- The destination airfield
- Route (STAR and approach)
- Descent wind forecast

The right panel of Figure A-2 illustrates what the IM display looks like after the pilot has used the keyboard to enter the airport identifier.



Figure A-2. Ownship page with no data entered (left) and airport identify entered (right).

The pilot next enters the Ownship route information by pressing the bezel button or soft-key for “ROUTE” in Figure A-2. Pressing either the bezel button or soft-key triggers the Ownship route page (shown in the left panel of Figure A-3).

The Ownship route page is structured to be as similar as possible to the FMS which displays the same information; that is, the STARs are on the left, approaches on the right, and all are listed in alphabetical order from top-to-bottom.

A page counter is shown at the top right (“PAGE 1 of 2” in this example), and the “PGUP” and “PGDN” bezel buttons at the top of the EFB are used to change pages.

The right panel of Figure A-3 illustrates that the approach procedure has been selected, and since only one transition was available, it was also automatically selected.

A green “ENTER” button appears at the bottom-right of the EFB indicating to the pilot that all required information has been entered. When the pilot presses the “ENTER” soft-key or bezel button, it returns the display to the Ownship page with all route data entered (shown in the left panel of Figure A-4).

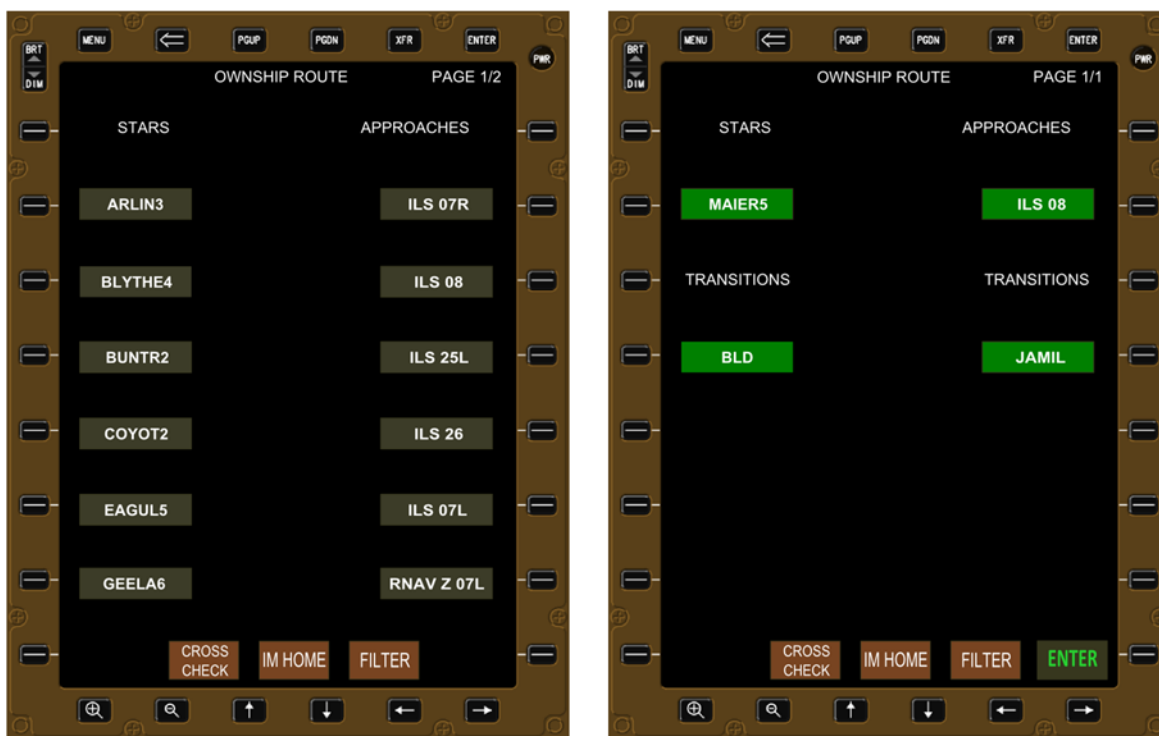


Figure A-3. Initiating (left) and entering (right) the Ownship route information.

The left panel of Figure A-4 illustrates the Ownship page with the airport and route information loaded. The pilot next presses either the bezel button or soft-key for “WIND”, causing the display shown in the right panel of Figure A-4 to appear.

In addition to the data fields for the descent and surface winds, a “LOAD DES FCST WIND” display also appears. This indicates to the pilot that there is an ACARS message available that can be loaded to the EFB by pressing either the bezel button or soft-key. If no ACARS message is available, the display would state “NO DES FCST WIND.”

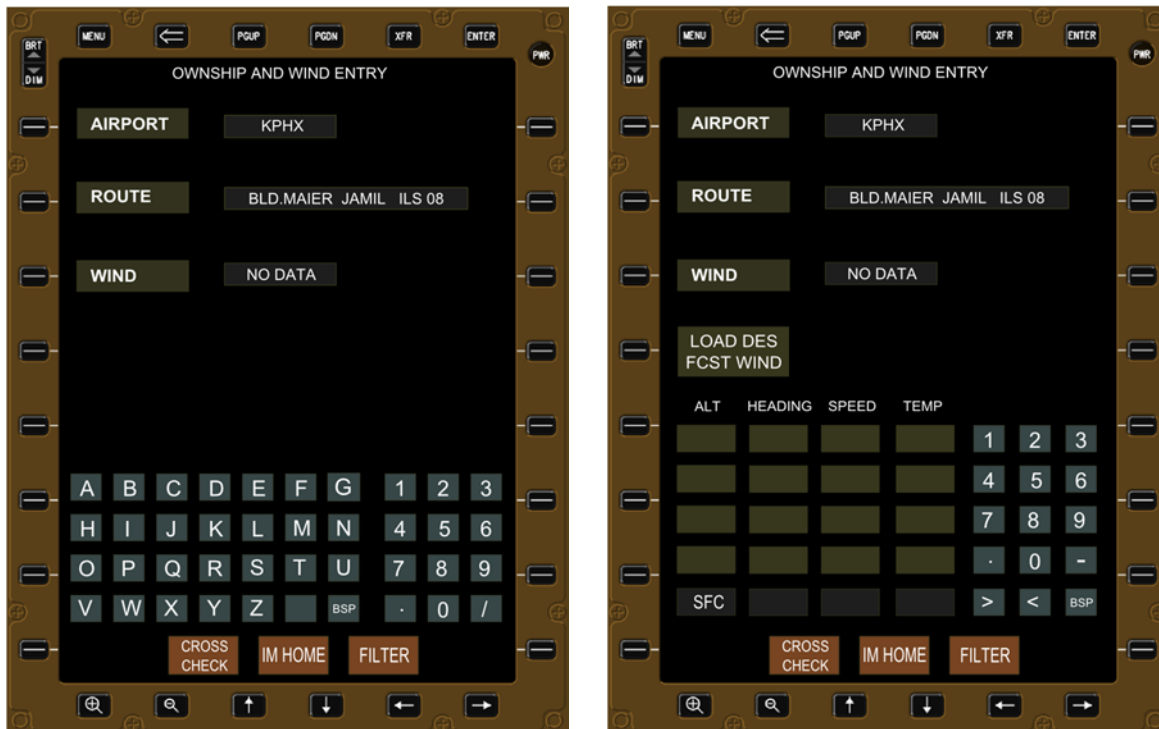


Figure A-4. Route entry complete (left) and initiating wind entry (right).

In the left panel of Figure A-5, the IM system does have a forecast descent wind available to be auto-loaded, which is indicated by the text “LOAD WIND FORECAST.” Pressing the button causes all the appropriate fields to be populated, except for the surface winds, which the pilot must enter manually. It also replaces the NO DATA message with the time stamp of the message used to provide the forecast descent wind information.

The right panel of Figure A-5 illustrates that the pilot has entered the surface wind and temperature information. A green “ENTER” button appears indicating all the required Ownship and wind information has been entered into the IM software.

Pressing the “ENTER” button causes the software to return to the IM home page and the Ownship information will be displayed (Figure A-7).

The figure consists of two side-by-side screenshots of a cockpit display titled "OWNSHIP AND WIND ENTRY". Both screens show the same data: AIRPORT: KPHX, ROUTE: BLD.MAIER JAMIL ILS 08, WIND: 101415Z, and a table of forecast winds at various altitudes.

ALT	HEADING	SPEED	TEMP
300	340	095	-44
240	300	046	-32
180	020	031	-21
100	040	027	-4
SFC			

At the bottom of the left screen, the "LOAD DES FCST WIND" button is highlighted. At the bottom of the right screen, the "ENTER" button is highlighted in green. Both screens also feature a numeric keypad and buttons for "CROSS CHECK", "IM HOME", and "FILTER".

Figure A-5. Descent winds loaded.

Figure A-6 illustrates what the Ownship home page looks like if the pilot returns to it after successfully entering all the data. This sequence could occur because the pilot wants to verify or change Ownship information, or update the descent and surface wind information. If the pilot does modify any Ownship or wind information, the green “ENTER” button will reappear.

OWNSHIP AND WIND ENTRY

AIRPORT: KPHX

ROUTE: BLD.MAIER JAMIL ILS 08

WIND: 101415Z

LOAD DES FCST WIND

ALT	HEADING	SPEED	TEMP
300	340	095	-44
240	300	046	-32
180	020	031	-21
100	040	027	-4
SFC	060	012	15

Buttons: CROSS CHECK, IM HOME, FILTER

Figure A-6. All Ownship data is entered.

Figure A-7 is the IM home page with all Ownship information entered, but without the IM clearance information entered. Indicators of this status to the pilot include a blue line around the Ownship box, the word “OWNSHIP” in green font, and the Ownship information displayed within the box (next waypoint, the STAR, and the approach).

The pilot next presses the bezel button or soft-key for “IM CLEARANCE,” which causes the IM clearance type page to appear (Figure A-8).

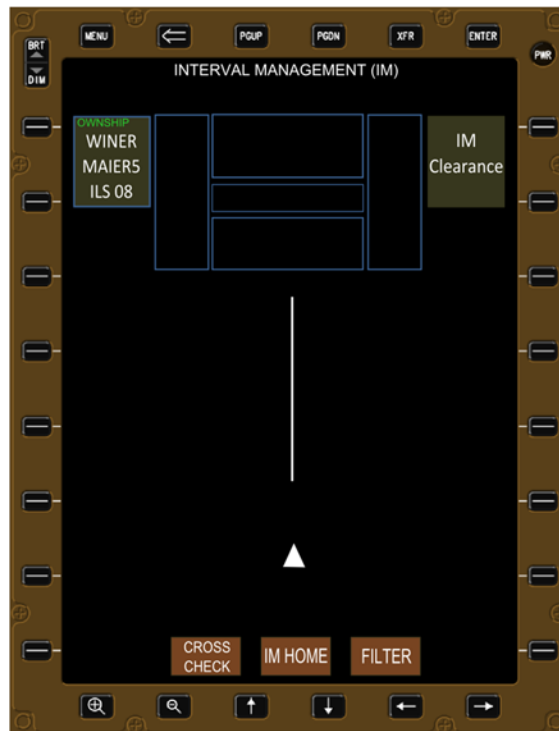


Figure A-7. IM home page with Ownship data entered.

A.1.3 Entering “IM CLEARANCE” Information

Figure A-8 depicts the page used by the pilot to select the IM clearance type issued by the controller. The text in the boxes aligns with the phraseology expected to be given by the controller, and not necessarily the name of the clearance type as defined in reference 3.

The pilot selects the type of clearance issued by the controller, and this presents a new page with only information required for that clearance type. In this example, the pilot will be issued a CROSS clearance type (also referred to as the achieve-by and maintain clearance).

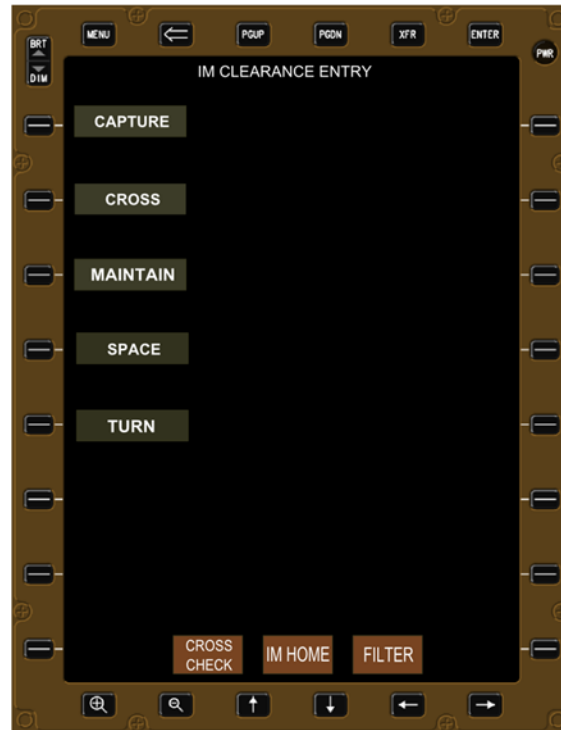


Figure A-8. IM clearance page to select clearance type.

Figure A-9 illustrates the data fields for the typical CROSS IM clearance type, and only the visible required and relevant data fields are shown for that clearance. The IM software automatically activates the next anticipated text box for data entry, in this case the ATC assigned spacing goal.

Figure A-10 illustrates the pilot has entered the number “78” via the keyboard, which is derived from the ATC issued IM clearance. The pilot then presses the bezel button or soft-key for “TARGET ID” to continue, which causes Figure A-11 to appear.

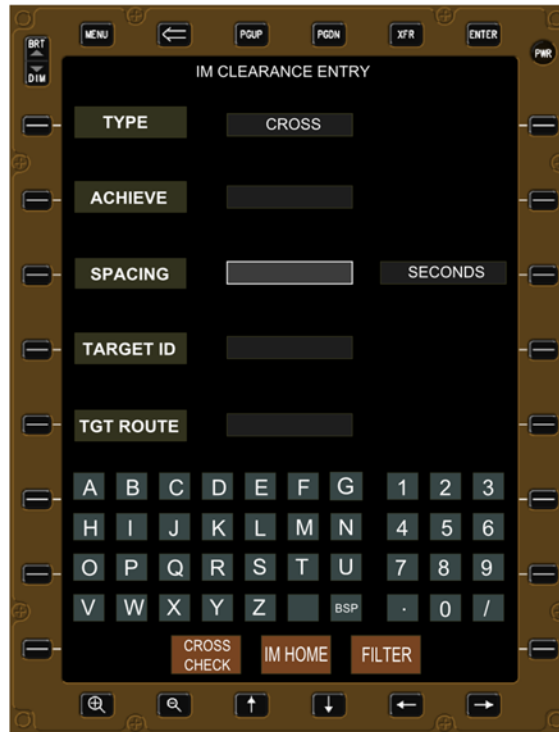


Figure A-9. IM clearance page for CROSS clearance type.

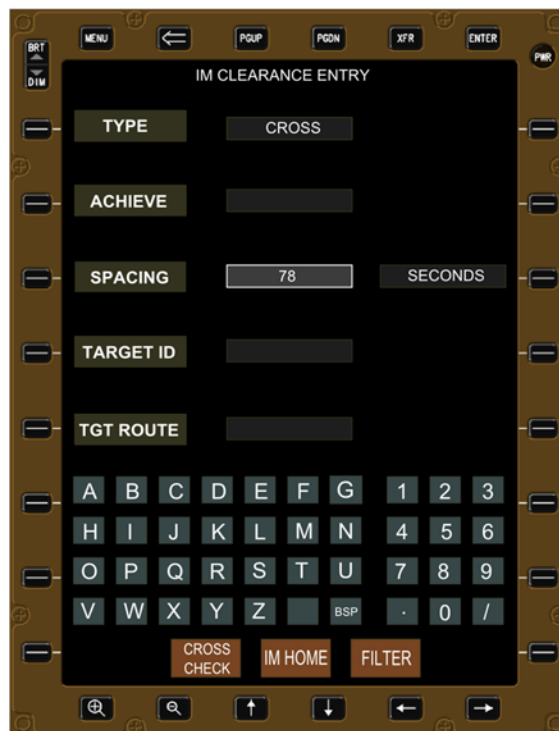


Figure A-10. IM clearance home page with assigned spacing goal entered.

Figure A-11 illustrates how all possible Target IDs (aircraft within ADS-B range) are listed in alphabetical order, from top to bottom, left to right. A page counter is shown in the upper right, and the “PGUP” and “PGDN” bezel buttons are used to change pages if required. The pilot presses the bezel button or soft-key for the correct Target aircraft ID, causing the display to return to the IM clearance home page (Figure A-12).

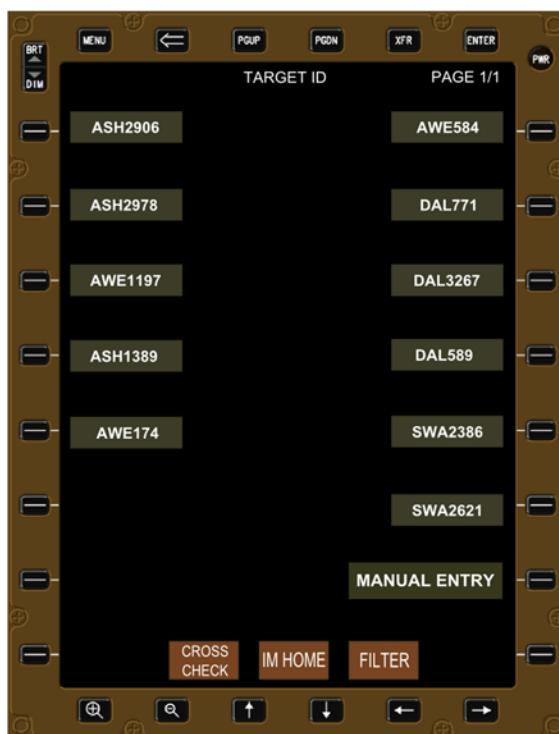


Figure A-11. List of possible Target aircraft within ADS-B range.

Figure A-12 illustrates the IM clearance home page after the pilot has selected the Target ID information from the list of available aircraft. The pilot then selects the bezel button or soft-key for “TGT ROUTE” (causing Figure A-14 to appear).

If the Target aircraft is not within ADS-B range of the Ownship aircraft, the pilot presses the “MANUAL ENTRY” button towards the bottom right of the EFB (shown in Figure A-11). This causes the display to return to the IM clearance home page, and the pilot uses the keyboard to manually enter the ID in the data field (Figure A-13).

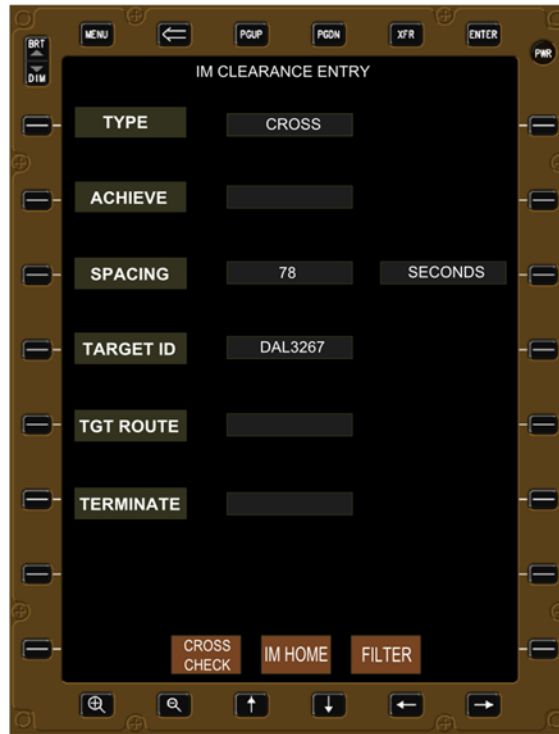


Figure A-12. IM clearance home page with the Target ID entered.

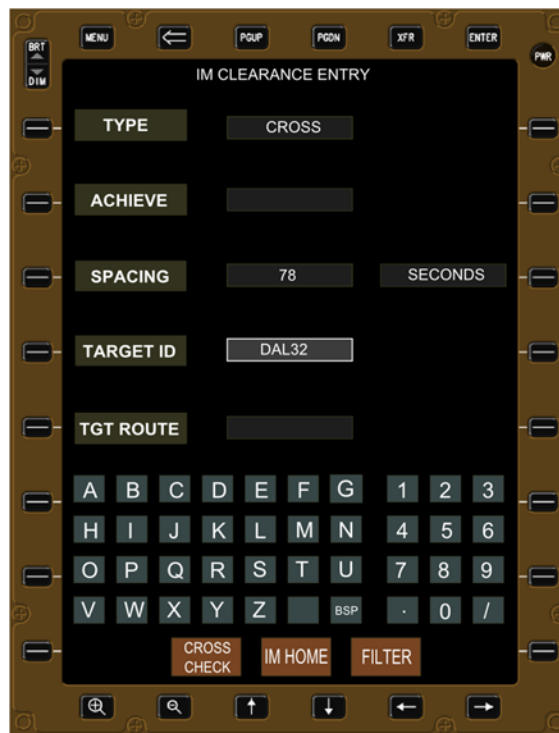


Figure A-13. Manually entering the Target ID when outside ADS-B reception range.

The left panel of Figure A-14 illustrates the Target route entry page, which includes setting as a default the Ownship approach procedure as the Target approach procedure. The pilot can manually override this setting; however the approaches selected for Ownship and Target aircraft must be to the same runway.

The right panel of Figure A-14 shows that the pilot has selected the bezel button of soft-key for the “EAGUL5” as the Target’s STAR. The green “ENTER” button appears once all required information has been selected, and pressing the bezel button or soft-key for “ENTER” returns the display to the IM clearance page (Figure A-15).

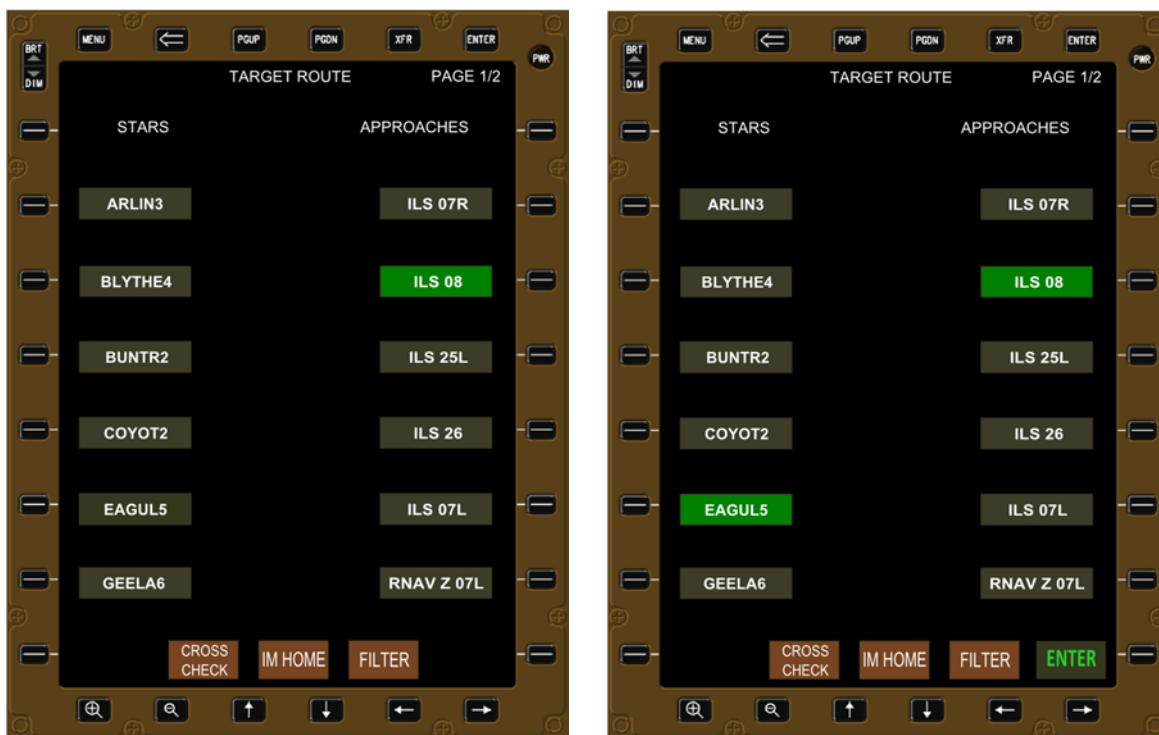


Figure A-14. Default Target approach (left) and STAR (right) entry page.

Figure A-15 shows the IM clearance home page after the Target route data has been entered. The “achieve-by” waypoint and the “TERMINATE” waypoint automatically default to the Ownship’s FAF waypoint, and can be manually overridden by the pilot.

The green “ARM” button appears at the bottom right of the EFB indicating to the pilot that all IM clearance information has been entered. Pressing the bezel button or soft-key for “ARM” transitions the IM software to the ARMED state.

Figure A-16 shows what appears if the pilot returns to the IM clearance page after successfully entering all the IM clearance data, for example to modify or change the IM clearance.

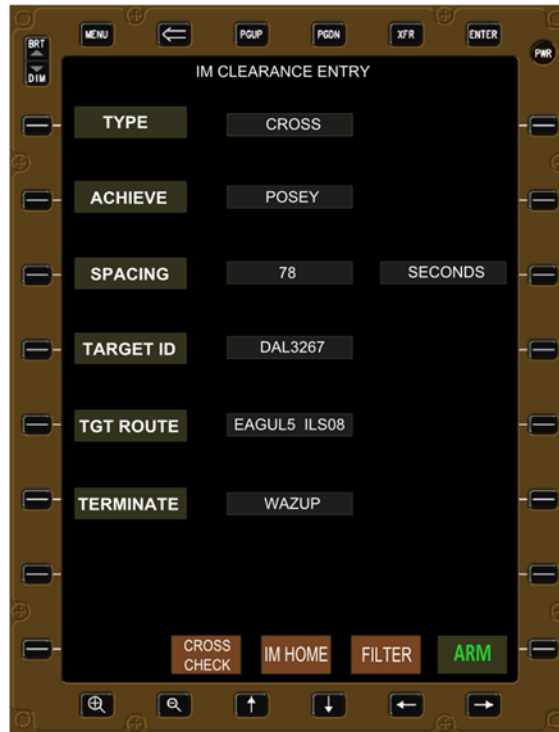


Figure A-15. IM clearance page with all information entered prior to ARM.

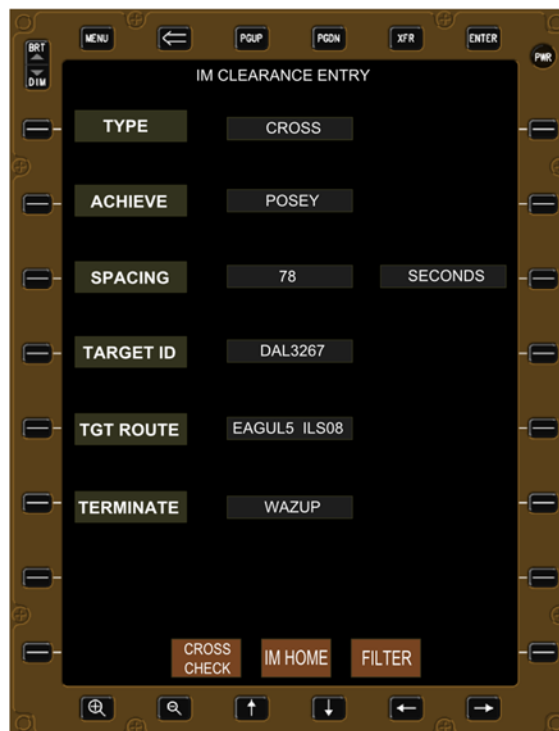


Figure A-16. Return to IM clearance page after the software was ARMED.

A.1.4 Transitions From the OFF State

- OFF to ARMED
 - Occurs when the flight crew manually presses the “ARM” button in the lower right corner of the EFB. The “ARM” button only becomes visible and selectable when all of the following conditions have been met:
 - Ownship data entered (for CROSS clearance type only; not required for others):
 - Airport
 - Route (both arrival and approach, and transitions if appropriate)
 - Forecast descent winds and temperature (if available)
 - Surface winds and temperature
 - IM clearance information entered:
 - Type of IM clearance
 - When to initiate IM (if appropriate for that clearance type)
 - Assigned spacing interval and type
 - Target aircraft identification
 - Target route (arrival and approach)
 - Achieve-by point (if appropriate for that type of clearance)
 - Terminate point (if appropriate for that type of clearance)

A.2 ARMED State

A.2.1 General Description

The IM system initiates the ARMED state when

- all Ownship (airport, route, and wind) and IM clearance data has been entered;
- the pilot presses the “ARM” button in the OFF state.

ASTAR algorithm:

- All data has been entered, the algorithm has been called, and either it is waiting for valid ADS-B track data from the Target aircraft, or there is valid ADS-B track data for the Target aircraft but it has not yet passed a waypoint with a speed constraint.

Displays (Figure A-17 and Figure A-18):

- “OWNSHIP” and “CLEARANCE” are shown in green to indicate completion.
- OWNSHIP and CLEARANCE data are shown in white for ease of viewing.
- “FAST/SLOW” and “EARLY/LATE” figures have labels but no data.
- Target information is shown in white below IM clearance information.
- The Target icon on traffic display is wrapped in white.

Messages:

- IM messages (if appropriate) are shown in white in lowest-middle box.
- A message should exist for every AVAILABLE criteria not met, for example:
 - WAITING TGT ADSB
 - WAITING TGT WPT

- OWNSHIP OFF ROUTE
- TGT OFF ROUTE
- TGT OFF VERT PATH
- INITIATE AT XXXXX

Alerts:

- There are no alerts in this state.

Figure A-17 illustrates the IM home page with all Ownship and IM clearance data entered, however the Target is not yet within ADS-B range of the Ownship aircraft.

Figure A-18 illustrates a valid ADS-B track file for the Target aircraft, however the Target has not yet passed a waypoint on the route that contains a speed constraint. Therefore the algorithm will not calculate the Target's estimated time of arrival, and therefore cannot calculate the IM-commanded speed.

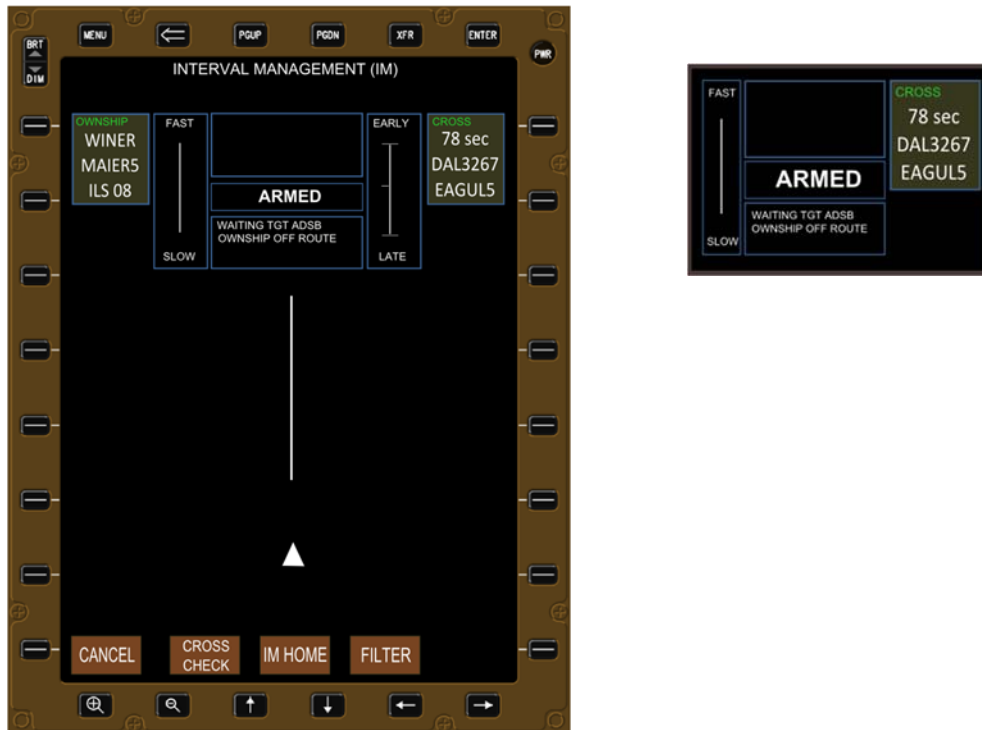


Figure A-17. Displays in ARMED state without Target data.

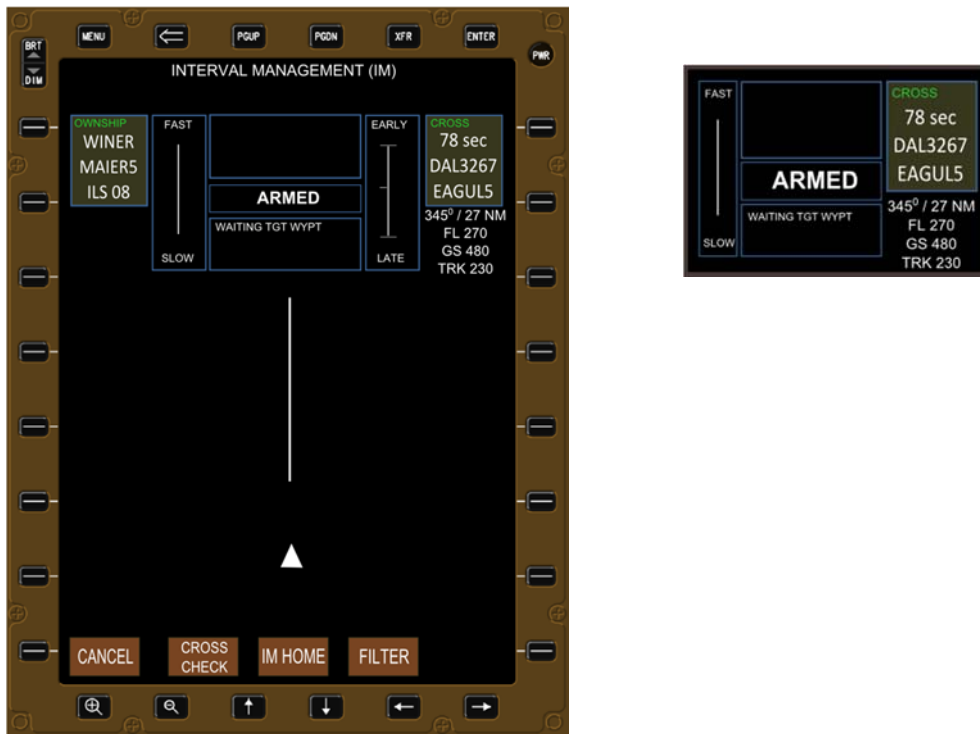


Figure A-18. Displays in ARMED state with Target data.

A.2.2 Transitions from the ARMED State

- ARMED to AVAILABLE
 - Occurs automatically when ASTAR is able to calculate a valid speed for spacing.
- ARMED to OFF
 - Occurs automatically when the aircraft crosses the terminate point.
 - Occurs manually when the pilot presses the “CANCEL” button (lower left of EFB).
- ARMED to UNABLE
 - Occurs automatically any time
 - the ASTAR algorithm experiences a failure;
 - the “TARGET BAD ROUTE” message is triggered;
 - the “OWNSHIP BAD ROUTE” message is triggered;
 - the forecast descent winds cause either the Ownship’s or the Target’s trajectory to not meet acceptable criteria.

A.3 AVAILABLE State

A.3.1 General Description

The IM system automatically transitions from the ARMED to the AVAILABLE state when

- the Ownship is on the lateral route defined in the IM software;
- the Ownship is proceeding to or has passed a waypoint with a speed constraint;
- the Target is within ADS-B range and a valid track file exists;
- the Target's trajectory can be calculated;
- the Target is laterally and vertically on the calculated trajectory.

ASTAR algorithm:

- The ASTAR algorithm is able to calculate the airspeed for the Ownship to fly.

Displays (Figure A-19):

- "OWNSHIP" and "CLEARANCE" are shown in green to indicate completion.
- "OWNSHIP" and "CLEARANCE" data is shown in white for ease of viewing.
- "FAST/SLOW" and "EARLY/LATE" figures have labels but no data.
- Target information is shown in white below IM clearance information.
- The Target icon on the traffic display is wrapped in white.

Messages:

- IM SPD AVAILABLE

Alerts:

- There are no alerts in this state.

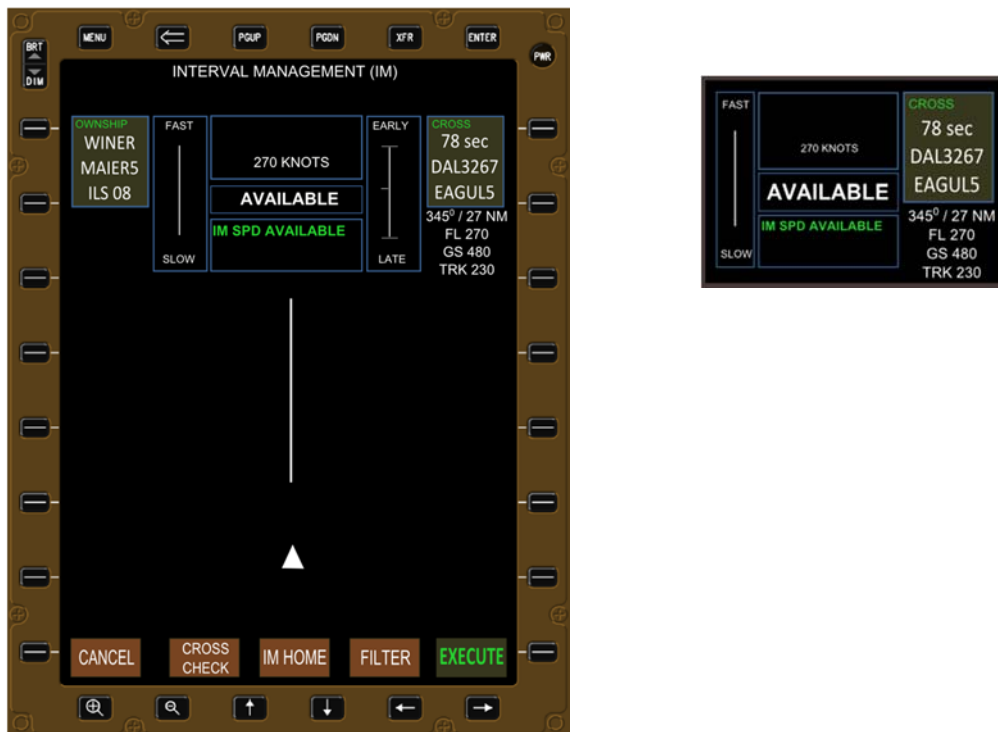


Figure A-19. Displays in AVAILABLE state.

A.3.2 Transitions from the AVAILABLE State

- AVAILABLE to OFF
 - Occurs automatically when the aircraft crosses the terminate point.
 - Occurs manually when the flight crew presses the “CANCEL” button.
- AVAILABLE to ARMED
 - Occurs automatically when any of the criteria specified to meet the AVAILABLE state are no longer met.
 - Occurs manually when the flight crew modifies the IM clearance.
- AVAILABLE to PAIRED
 - Occurs manually when the flight crew presses the “EXECUTE” button.
- AVAILABLE to UNABLE
 - Occurs automatically when the ASTAR algorithm experiences a failure, a “TARGET BAD ROUTE” or “OWNSHIP BAD ROUTE” condition exists, or the trajectory of either aircraft is no longer flyable due to sensed or forecast winds.

A.4 PAIRED State

A.4.1 General Description

The IM system transitions to the PAIRED state when

- the pilot manually presses the “EXECUTE” button in the AVAILABLE state.

ASTAR algorithm:

- The ASTAR algorithm is able to calculate the airspeed for the Ownship to fly.

Displays (Figure A-20):

- The IM-commanded speed is shown in large green numbers.
- The IM status is shown in green as PAIRED.
- “FAST/SLOW” also contains a green triangle for IM instantaneous speed.
- The “EARLY/LATE” figure is now populated (not shown).
- Target information is shown in green below the IM clearance information.
- The Target icon on traffic display is now wrapped in green (previously in white).
- A “SUSPEND” soft-key is added to lower-right.

Messages:

- Advisory messages possible in this state include:
 - TOO FAST (appears 10 sec after “FAST/SLOW” indicator)
 - TOO SLOW (appears 10 sec after “FAST/SLOW” indicator)
 - SPEED LIMITED
 - COMPUTING SPEED
 - SPC ERROR TOO LRG

Alerts:

- Speed change:
 - A new IM-commanded speed is shown in reverse video for the first 10 sec on both the EFB and CGD.
 - The display returns to normal when that speed is set in the MCP.
 - A new IM-commanded speed not set in the MCP for greater than 10 sec is shown in flashing video on both the EFB and CGD.
 - The display returns to normal when that speed is set in the MCP.
- Speed deviation:
 - The “FAST/SLOW” indicator includes a “+xx” immediately below the word “FAST,” or a “-xx” immediately above the word “SLOW,” if the aircraft’s airspeed is greater than 10 kt (or 0.02 M) different than the IM instantaneous speed.
 - The IM text box displays either “TOO FAST” or “TOO SLOW” if the aircraft’s airspeed is greater than 10 kt (or 0.02 M) different than the IM instantaneous speed.

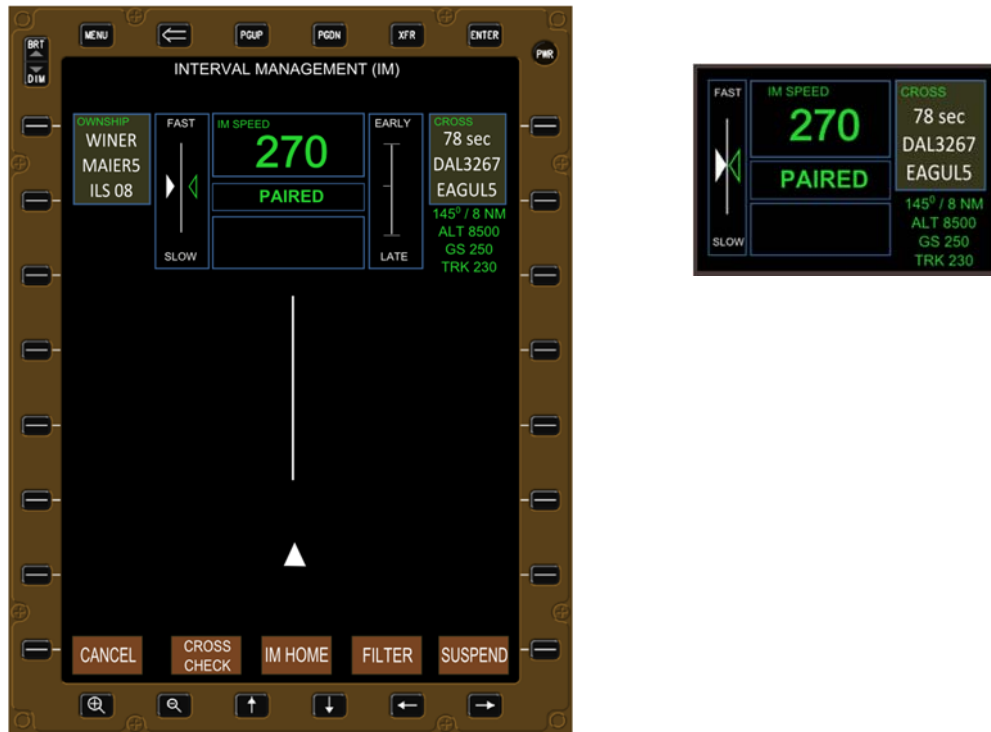


Figure A-20. Displays in PAIRED state.

A.4.2 Transitions from the PAIRED State

- PAIRED to OFF
 - Occurs automatically when the aircraft crosses the terminate point.
 - Occurs manually when the flight crew presses the “CANCEL” button.
- PAIRED to ARMED

- Occurs manually when the flight crew modifies either the Ownship or IM clearance information.
- PAIRED to SUSPENDED–ARMED
 - Occurs automatically when any of the following occur:
 - The Ownship flight path is no longer on the calculated trajectory.
 - The Target flight path is no longer on the calculated trajectory.
 - The spacing error becomes too large to resolve in the remaining trajectory.
 - The Target data is lost.
- PAIRED to SUSPENDED–AVAILABLE
 - Occurs manually when all of the following conditions are met:
 - All the criteria for a valid IM speed are still met.
 - The flight crew presses the “SUSPEND” button (lower right of EFB).
- PAIRED to UNABLE
 - Occurs automatically when the ASTAR algorithm experiences a failure.

A.5 SUSPENDED–ARMED State

A.5.1 General Description

The IM system automatically transitions to the SUSPENDED–ARMED state when

- the Ownship flight path is no longer on the calculated trajectory;
- the Target flight path is no longer on the calculated trajectory;
- the Target state data is no longer available;
- the spacing error becomes too large to resolve in the remaining trajectory.

ASTAR algorithm:

- The ASTAR algorithm can calculate both the Ownship and Target trajectories; however one or both of the aircraft are not on their respective trajectory, or the spacing error is too large to resolve in the remaining trajectory.

Displays (Figure A-21):

- The IM-commanded speed is removed.
- The IM status shown is in white as “SUSPENDED.”
- The “FAST/SLOW” and “EARLY/LATE” figures have information removed.
- Target information and the Target icon are shown in white.
- The “SUSPEND” soft-key at lower-right is removed (area now empty).

Messages:

- Messages are shown indicating reason for SUSPENDED state, for example
 - OWSHIP OFF ROUTE
 - TGT OFF ROUTE

- TGT OFF VERT PATH
- SPC ERROR TOO LRG
- TGT ADSB LOST (intentionally different than WAITING TGT ADSB)

Alerts:

- Speed change:
 - No longer shown
- Speed deviation:
 - No longer shown

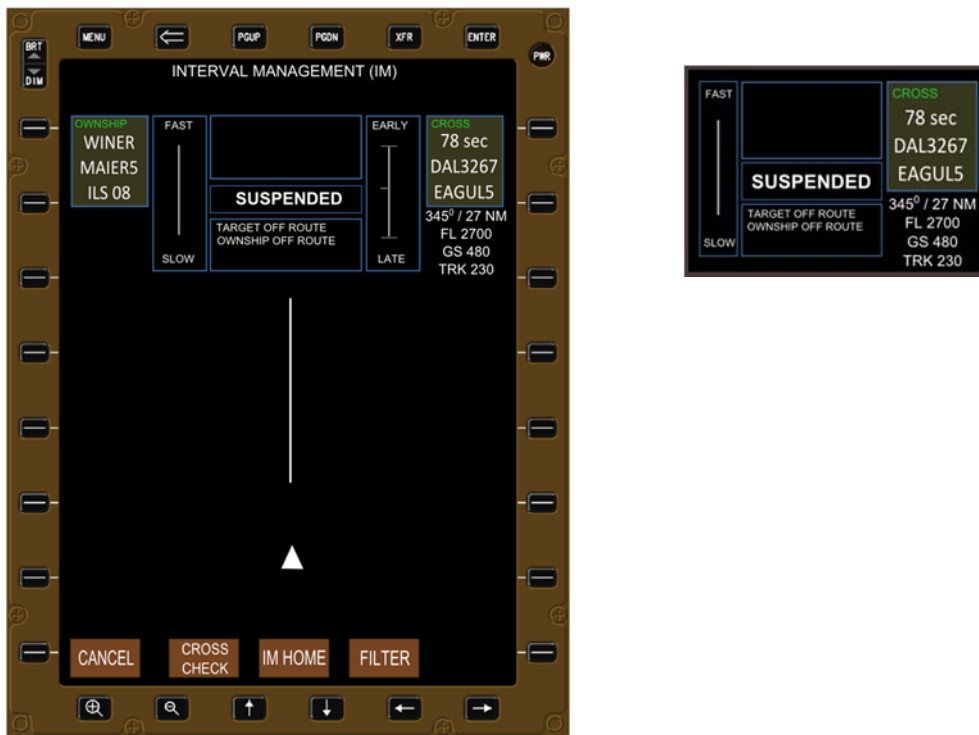


Figure A-21. Displays in SUSPENDED-ARMED state.

A.5.2 Transitions from the SUSPENDED-ARMED State

- SUSPENDED-ARMED to OFF
 - Occurs automatically when the aircraft crosses the terminate point.
 - Occurs manually when the flight crew presses the “CANCEL” button.
- SUSPENDED-ARMED to ARMED
 - Occurs manually when the flight crew modifies the IM clearance.

- SUSPENDED–ARMED to SUSPENDED–AVAILABLE
 - Occurs manually when all of the criteria for a valid IM operation are met.
- SUSPENDED–ARMED to UNABLE
 - Occurs automatically when the ASTAR algorithm experiences a failure.

A.6 SUSPENDED–AVAILABLE State

A.6.1 General Description

The IM system manually transitions to the SUSPENDED–AVAILABLE state when the pilot presses the “SUSPEND” button while in the PAIRED state.

The system automatically transitions from SUSPENDED–ARMED to SUSPENDED–AVAILABLE state when all criteria are met for valid IM operation while in the SUSPEND–NOT AVAILABLE state.

ASTAR algorithm:

- the ASTAR algorithm can calculate both the Ownship and Target trajectories and a valid IM speed can be calculated.

Displays (Figure A-22):

- The IM-commanded speed is shown in small font.
- a message of “IM SPD AVAILABLE” appears.
- The IM status is shown in white as “SUSPENDED.”
- The “FAST/SLOW” and “EARLY/LATE” figures have information removed.
- The Target information and Target icon are shown in white.
- A green “RESUME” soft-key is added to the lower-right.

Messages:

- IM SPD AVAILABLE

Alerts:

- None

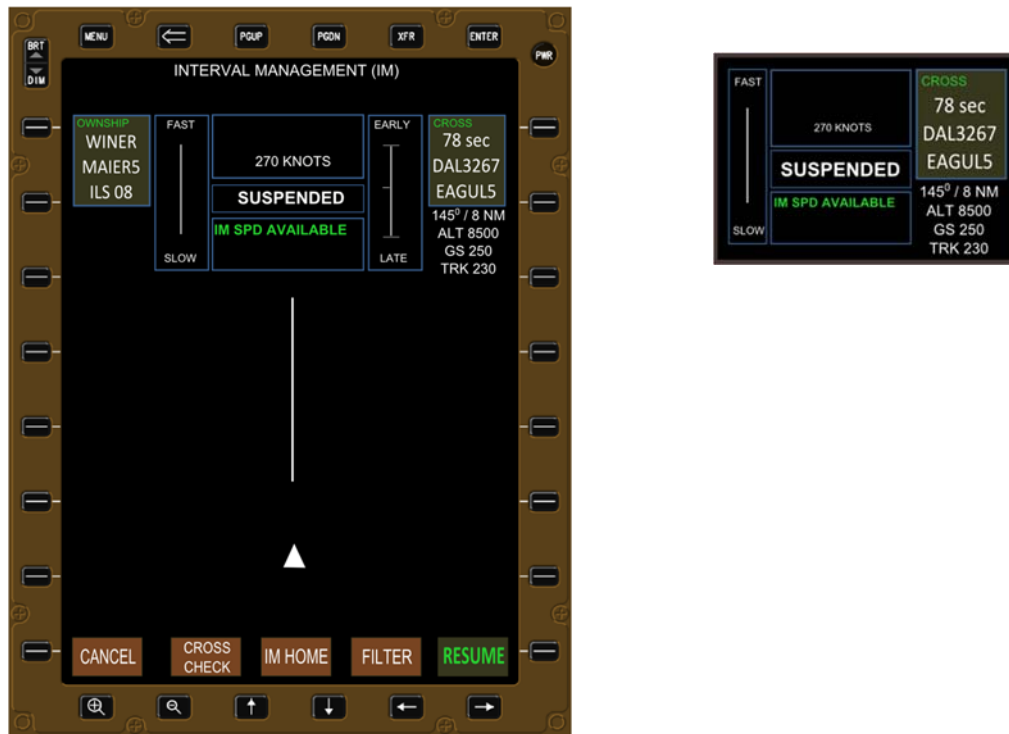


Figure A-22. Displays in SUSPENDED-AVAILABLE state.

A.6.2 Transitions from the SUSPENDED-AVAILABLE State

- SUSPENDED-AVAILABLE to OFF
 - Occurs automatically when the aircraft crosses the terminate point.
 - Occurs manually when the flight crew presses the “CANCEL” button.
- SUSPENDED-AVAILABLE to ARMED
 - Occurs manually when the flight crew modifies the IM clearance.
- SUSPENDED-AVAILABLE to PAIRED
 - Occurs manually when the flight crew presses the “RESUME” button.
- SUSPENDED-AVAILABLE to SUSPENDED-ARMED
 - Occurs automatically when any of the following conditions occur:
 - The Ownship flight path is no longer on the calculated trajectory;
 - The Target flight path is no longer on the calculated trajectory;
 - The spacing error becomes too large to resolve in remaining trajectory;
 - The Target data is lost.
- SUSPENDED-AVAILABLE to UNABLE
 - Occurs automatically when the ASTAR algorithm experiences a failure.

A.7 UNABLE State

A.7.1 General Description

The IM system automatically transitions to the UNABLE state when

- The IM equipment fails;
- The database used by the IM software is not current;
- The Ownship or Target bad route is defined;
- The Ownship or Target aircraft data is invalid or incomplete;
- Forecast descent winds cause the Ownship or Target trajectory to not meet flyable criteria.

ASTAR algorithm:

- The ASTAR algorithm is not able to function.

Displays (Figure A-23):

- The IM-commanded speed is removed.
- The IM status is shown in white as “UNABLE.”
- The “FAST/SLOW” and “EARLY/LATE” figures have information removed.
- The Target information and Target icon are removed.
- No soft-key is visible at lower-right (normally “SUSPEND” or “RESUME”).

Messages:

- Messages are shown indicating reason for the UNABLE state, for example
 - OWNSHIP BAD ROUTE
 - TARGET BAD ROUTE
 - EQUIP FAILURE
 - OWN RTE BAD-WIND
 - TGT RTE BAD-WIND

Alerts:

- Speed change:
 - No longer shown
- Speed deviation:
 - No longer shown

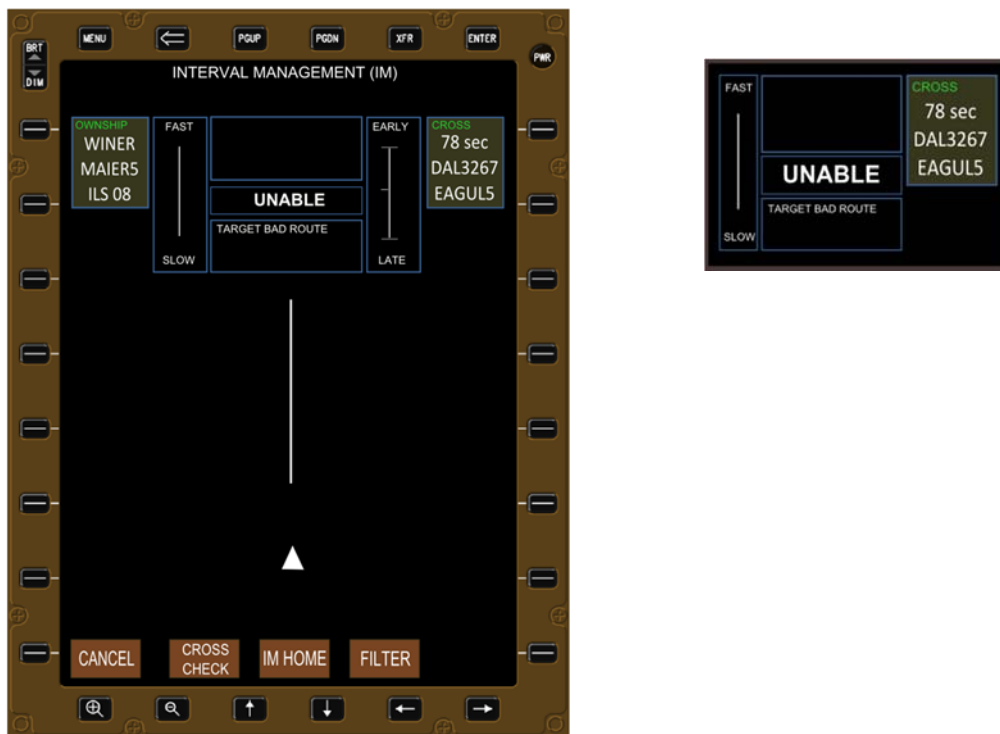


Figure A-23. Displays in UNABLE state.

A.7.2 Transitions from the UNABLE State

- UNABLE to OFF
 - Occurs automatically when the Ownship aircraft crosses the terminate point.
 - Occurs manually when the flight crew presses the “CANCEL” button.

Appendix B MAINTAIN Clearance Example

This appendix illustrates an example of the pilot entering maintain type of IM clearance. The instruction from air traffic control to the pilot is to maintain the current spacing behind Air Shuttle (ASH) 2978. In this case, the Ownship and Target aircraft must be on the same route, and the pilot is not required to enter Ownship or wind information into the IM software. (Note however, that the display used in this appendix shows the pilot has entered Ownship information. Although Ownship information is not required when it is on the same route as the Target, it is assumed that the pilots would enter that information prior to the controller issuing the IM clearance, so there will be times where the Ownship data is not needed.)

The left panel of Figure B-1 illustrates the IM Home Page with Ownship data entered (although not required for a MAINTAIN clearance type). Pressing the IM Clearance soft-key or bezel button in the left panel causes the IM clearance type entry page to appear (the right panel of Figure B-1). The pilot presses the bezel button or soft-key for MAINTAIN, and the display now shows all the required data elements for that type of clearance (left panel of Figure B-2).

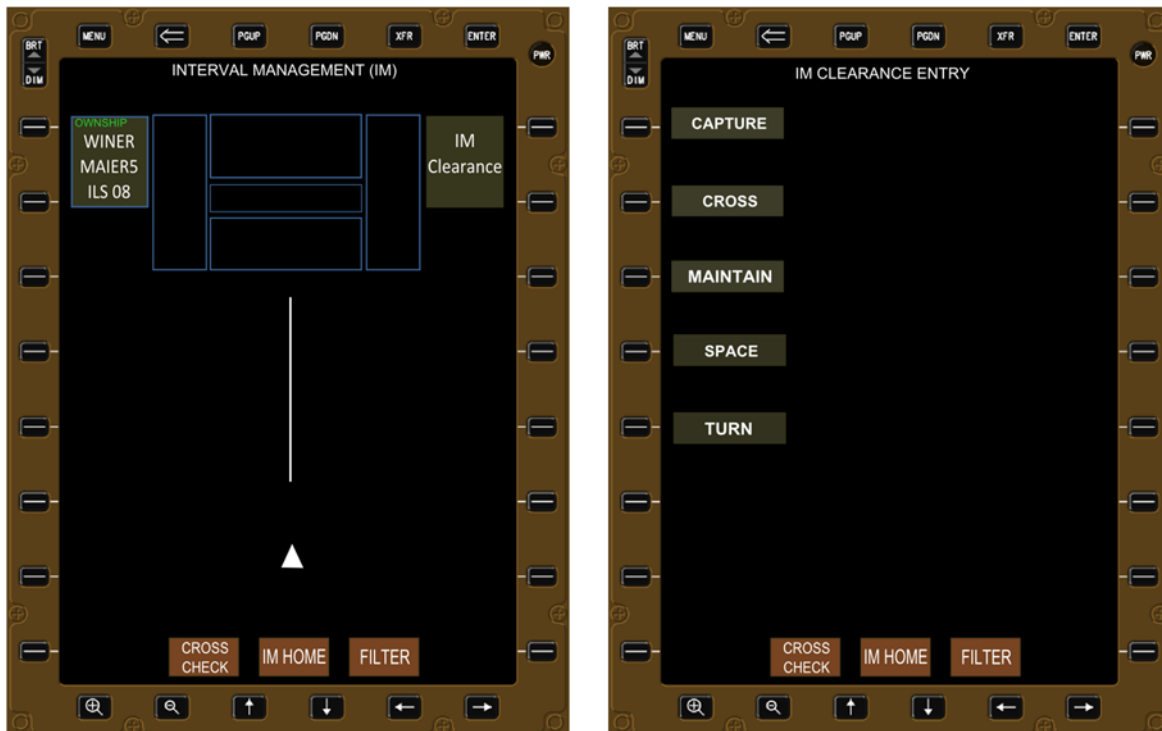


Figure B-1. IM home page (left) and IM clearance type entry page (right).

The MAINTAIN clearance type instructs the spacing algorithm to maintain the current time or distance (as assigned by ATC) behind the Target aircraft. The default value is time (shown as SECONDS in the left panel of Figure B-2), and can be manually changed by the pilot by selecting that bezel button or soft-key to cycle between the two options.

To enter the Target identification, the pilot presses that bezel button or soft-key (left panel of Figure B-2), causing a list of all valid ADS-B track files to appear (right panel of Figure B-2). The pilot presses the appropriate bezel button or soft-key for the ATC-assigned Target aircraft's identification, causing that information to be entered on the IM clearance entry page (left panel of Figure B-3).

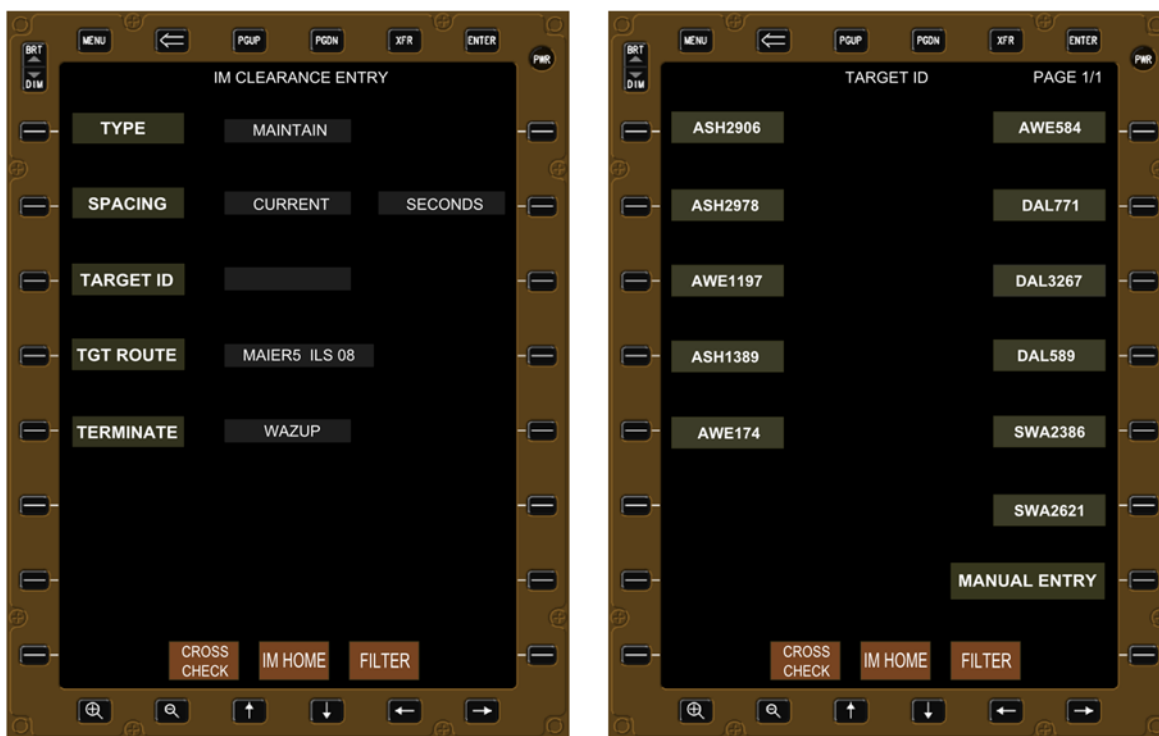


Figure B-2. Target ID entry (left) and list of aircraft within ADS-B range (right).

The Target aircraft route and terminate waypoint is automatically populated by the IM software to be the same as the Ownship information (if entered), and can be manually changed by the pilot (left panel of Figure B-2).

In this example, since the Target aircraft was within ADS-B reception range and all the criteria to conduct an IM operation were met, the software immediately transitions from OFF to ARMED to AVAILABLE (right panel of Figure B-3).

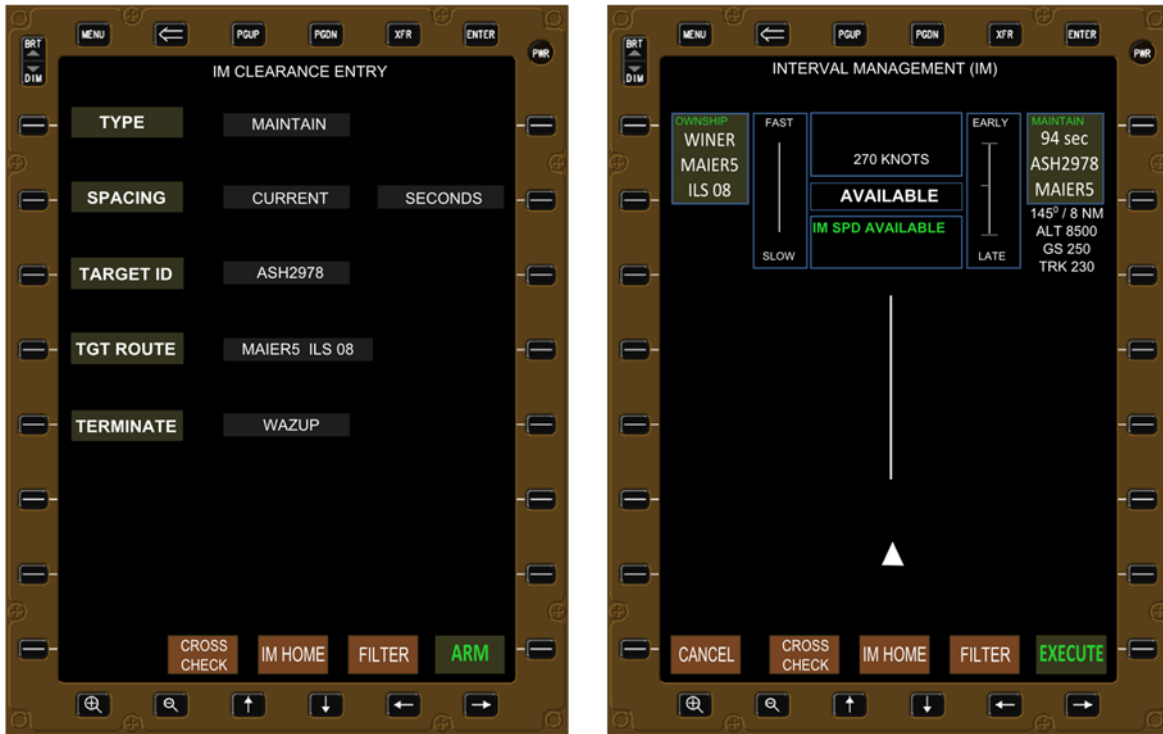


Figure B-3. Maintain clearance data entered (left) and operation available (right).

Appendix C IM-Commanded Speed Change Example

The figures show a change to the IM-commanded speed, and the associated displays and messages when there is a deviation between the aircraft's speed and the IM instantaneous speed.

Figure C-1 shows a snap-shot of the EFB immediately after the IM-commanded speed has changed from 270 kt to 240 kt (shown in the left panel of Figure C-1 in large green font).

The hollow green triangle is the IM instantaneous speed as well as the reference speed (remains fixed in the middle of the vertical FAST/SLOW display). The IM instantaneous speed takes the discrete IM-commanded speed, adds compensation for the delay due to pilot recognition and reaction time, then estimates the deceleration rate of the aircraft to produce a smooth and continuous value. Therefore the left panel of Figure C-1 could be the indication immediately after the IM-commanded speed changed from 270 to 240 kt, the aircraft was decelerating at the rate predicted by ASTAR, or the aircraft has stabilized at 240 kt.

The right panel of Figure C-1 shows that the aircraft is decelerating slower than ASTAR predicted; the aircraft's airspeed (indicated by the solid white triangle) is above the reference speed (the hollow green triangle indicates the IM instantaneous speed). Using the FAST/SLOW convention, when the pilot moves the control device (the throttles) towards the reference speed, the throttles are moved aft which slows the aircraft as desired.



Figure C-1. IM-commanded speed change (left) and FAST/SLOW indication (right).

The left panel of Figure C-2 illustrates the display and message when the difference between the aircraft's speed and the IM instantaneous speed is greater than 10 kt. In this example, the aircraft is flying 15 kt faster than the ASTAR predicated IM instantaneous speed, causing the aircraft's airspeed icon (the solid white triangle) to be above the IM reference speed icon (the hollow green triangle). When the difference between the two airspeeds is greater than 10 kt, the numerical value of the difference appears just below the word "FAST" (shown as "+15"), and an "AIRCRAFT TOO FAST" message also appears.

The right panel of Figure C-1 illustrates the same example for when the aircraft is 15 kt slower than the IM instantaneous speed.



Figure C-2. Aircraft faster (left) and slower (right) than IM instantaneous speed.

Appendix D Pilot-Selectable Filters

This section shows four examples of how pilot-selectable filters can be used to tailor the information shown on the EFB and CGD. Although the figures in this section are based on a current avionics product, the software implemented for research within NASA will have button select displays similar to the green buttons in Figure A-3 and Figure A-14. The figures are:

- 1) Figure D-1 shows that the filter for the Target's bearing, range, altitude, ground speed, and ground track is selected (the displays shown throughout the rest of this document).⁵
 - This configuration was used predominately throughout this document.
- 2) Figure D-2 illustrates the EFB when the Target information filter is deselected (data removed from EFB and CGD).
- 3) Figure D-3 shows that multiple filters are selected, to include routes and waypoints.
- 4) Figure D-4 illustrates an expanded MAP ONLY mode.

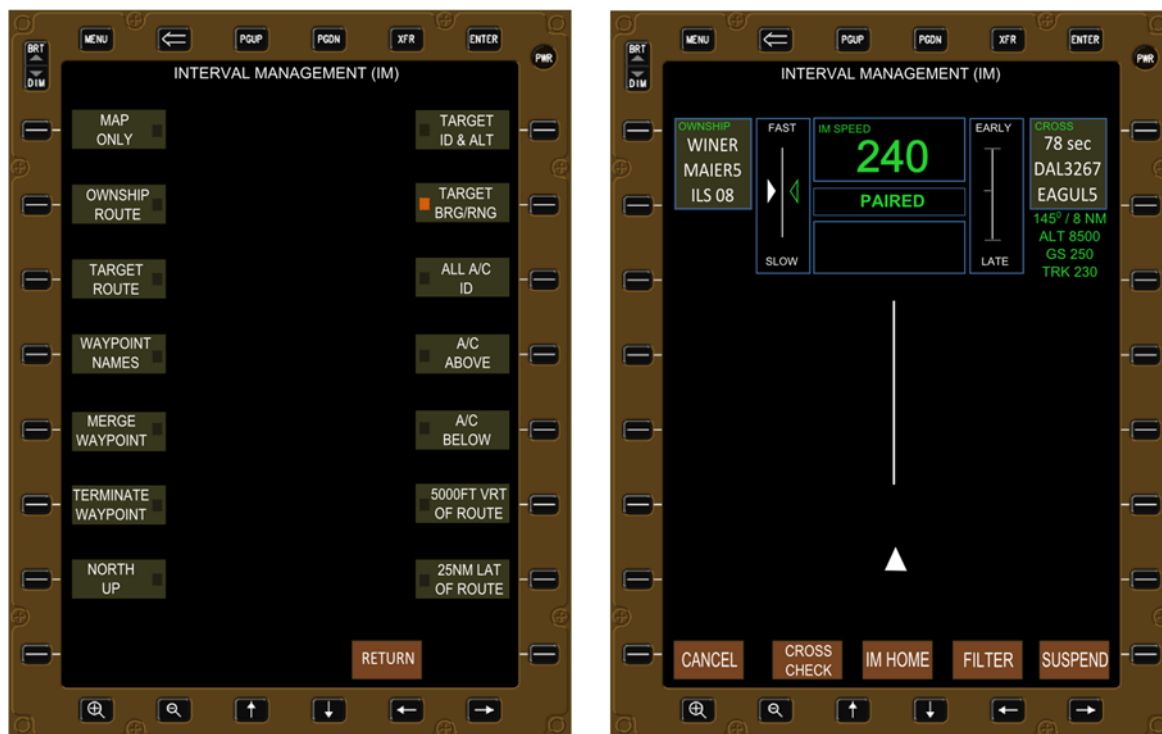


Figure D-1. Target Information filter and corresponding display.

⁵The Target information is the only data displayed on both the EFB and CGD; all other filters only impact the EFB display.

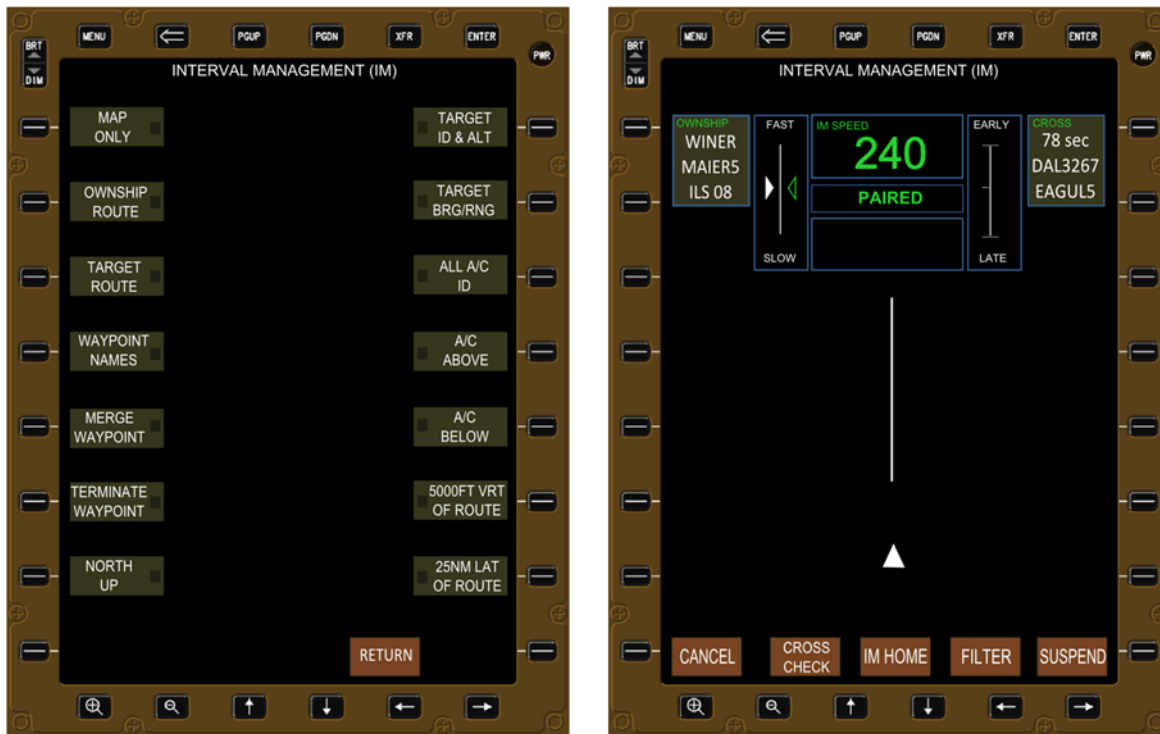


Figure D-2. No filters selected and corresponding display.

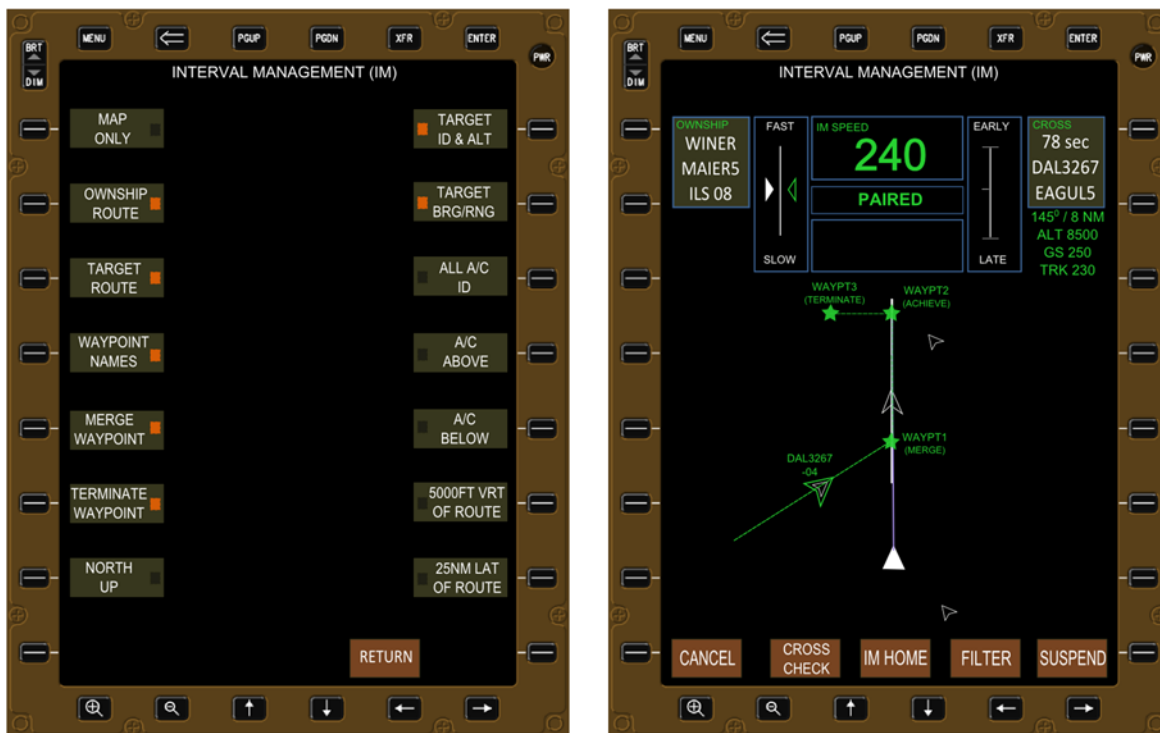


Figure D-3. Multiple filters selected and corresponding display.

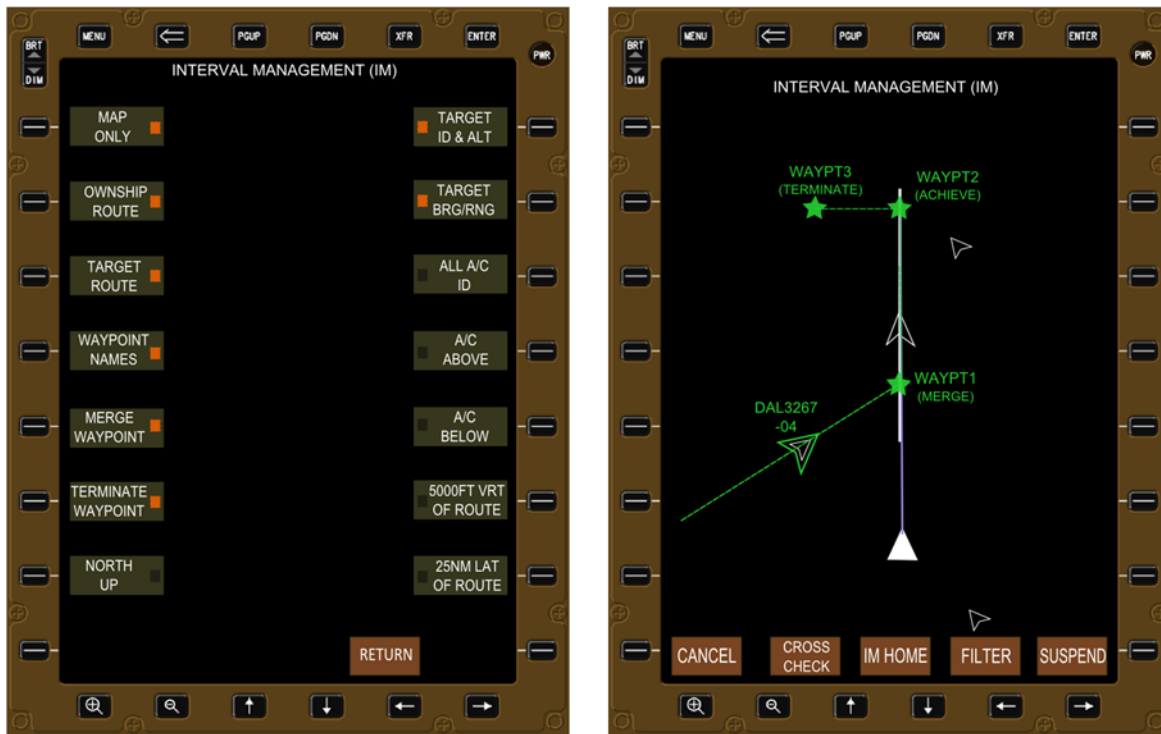


Figure D-4. MAP ONLY filter selected and corresponding display.

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